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A conjunctive groundwater and surface water model of the upper part of the Mark Twain Watershed in northeast Missouri

Chu-Lin Cheng
Iowa State University

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Chu-Lin Cheng

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Program of Study Committee:
William W. Simpkins, Major Professor
Richard C. Schultz, Committee member
Thomas M. Isenhart, Committee member

Iowa State University

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Graduate College
Iowa State University

This is to certify that the master's thesis of

Chu-Lin Cheng

has met the thesis requirements of Iowa State University

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ABSTRACT

The Mark Twain Lake Watershed in northeastern Missouri is the main source of water supply for 16 water districts in the region and is suffering serious water quality issues. A steady-state, analytical-element, groundwater flow model GFLOW simulation was constructed in the Mark Twain Lake watershed in claypan soils of northeastern Missouri including the Crooked Creek monitoring site. The objectives of the study were to establish a conjunctive surface water and groundwater model for central part of the Mark Twain Lake Watershed region using GFLOW.

The near-field region consisted of 3,000 km^2 area within a domain representing approximately 6,000 km^2. The model was calibrated using 6 hydraulic head targets, 4 lake stage targets, and 5 baseflow flux targets by trial-and-error, UCODE, and PEST simulations. Parameters refined through the automatic technique yielded optimal values of 5 m/day for regional hydraulic conductivity for the model domain, 100 m/day for inhomogeneities (alluviual deposits along streams), and a recharge rate of 0.000195 m/yr (about 7% of mean annual precipitation). Model results indicated that Mark Twain Lake is a surface-water-dominated lake. Sixty-seven percent of the water arriving at the Mark Twain Lake is from streamflow and 22 percent from precipitation, whereas only 11 percent is from groundwater. The lake received about ten times more groundwater inflow (101,000 m^3/day, 11 percent) than outflow (18,000 m^3/day, 2 percent). More than ninety-eight percent of water moving out of the lake from is evapotranspiration (210,000 m^3/day) and stream flow (731,000 m^3/day), whereas only 2 percent (18,000 m^3/day) is lost from groundwater.

The groundwater flow and surface water discharge predicted by the GFLOW simulations probably reflect the strong influence of claypan soils in the study area, where overland flow comprises most of streamflow. According to the particle tracking results, NPS pollutants in groundwater are transported primarily downstream through highly permeable, alluvial channels. Groundwater inflow to the stream emanates only from a small zone immediately adjacent to the stream. These results suggest that the net effect of riparian buffers on NPS pollutants in the region could be increased by expanding buffers outward from the creek edge to the edge of the alluvial deposits along the valley.

INTRODUCTION

In the Corn Belt region of the United States, fertilizer and herbicide contamination of streams is widely recognized as one of the major environmental impacts of row crop production (Thurman et al., 1991; Missouri Department of Natural Resources, MDNR, 1999; MDNR, 2001; Simpkins et al., 2002; Lerch and Blanchard, 2003; Lerch and Blanchard, 2004; Schultz et al. 2004). The Mark Twain Lake Watershed in northeastern Missouri (Figure 1) is the main source of water supply for 16 water districts and communities in the region and is suffering serious water quality issues (MDNR, 2005; United States Environmental Protection Agency, USEPA, 2005). With a surface area of 7,530 hectares (18,600 acres) and a maximum depth of 26 m (85 ft), Mark Twain Lake is the largest reservoir in northern Missouri and located in Monroe and Ralls Counties (Figure 2). The lake was initially proposed to relieve flooding problems on the Salt River. The U.S. Army Corps of Engineers completed construction in 1983, and now the lake provides drinking water, flood control, electricity and recreational opportunities for Missourians. The lake watershed covers 600,000 hectares (1,472,000 acres), with just over one-half of that covered by row crop agriculture. Grassland and prairie cover one-quarter of the land in the watershed. These land uses are typical of northern Missouri, where the soils are well developed and rich in nutrients needed for plant growth (Lakes of Missouri Volunteer Program, LMVP, 2005a; MDNR, 2005).

During the past two decades, Mark Twain Lake has being threatened by nonpoint-source (NPS) contaminants, such as agrichemicals, nutrients, and sediments. Upland and bottom-lands are intensively cropped and agricultural chemicals are used extensively.

Shelby and Monroe counties are among the top 10 hog-producing counties in Missouri and animal waste could provide contaminants to the lake (Clarence Cannon Wholesale Water Commission, CCWWC, 2005; LMVP, 2005b; USEPA, 2005). Hence, the Mark Twain Water Quality Demonstration Project (a subproject of Mark Twain Water Quality Initiative) expedites the adoption of innovative best management practices (BMPs) through technical assistance to producers. Led by the Natural Resources Conservation Service, the original project targeted portions of seven counties draining into the Mark Twain Lake. The focus has been expanded to include a major portion of the Upper Salt River Basin (USEPA, 2005).

The Mark Twain Lake Watershed is located in the Central Claypan Land Resources Area (MLRA 113, Major Land Resources Areas) (Missouri Cooperative Soil Survey, 2005; Natural Resources and Conservation Services, NRCS, 2005) (Figure 3). Studies have demonstrated that field runoff represents the primary hydrologic mechanism responsible for fertilizer and herbicide transport from agricultural fields to streams in this watershed (Tindall and Vencill, 1995; Lerch and Blanchard, 2003; Lerch and Blanchard, 2004; Seobi et al., 2005). Contamination of groundwater occurs through preferential flowpaths in the claypan soils (Tindall and Vencill, 1995; Kelly and Pomes, 1997)

Riparian buffers systems combine woody and non-woody plant material to address chemicals and sediment in surface runoff and runoff from adjacent cropped fields (Figure 4). Riparian buffers also stabilize streambanks, improve aquatic and terrestrial habitat and slow flood flows. Furthermore, they provide a low-cost way to control and reduce contaminants introduced into the surface water and groundwater system. Studies of riparian buffers improving reduction of NPS contaminants have been reported throughout the United States (Schnabel et al., 1997; Inamdar et al., 1999a, 1999b; Gold et al., 2001; Addy et al., 2002;

McGlynn and Seibert, 2003; Puckett, 2004; Vidon et al., 2004; Puckett and Hughes, 2005; Seobi et al., 2005). Intensive studies of buffers in Bear Creek, central Iowa, have shown effective conservational control, such as sediment erosion, stream bank stabilization and nitrate concentration reduction (Johnston, 1998; Andress, 1999; Simpkins et al., 2002; Wineland, 2002; Zaimes et al., 2002; Spear, 2003).

PURPOSE AND SCOPE

Because most of the drinking water in the northeast region of Missouri comes from reservoirs, a large percentage of the population is affected by the water quality in contributing watersheds. Riparian buffers may reduce nonpoint source pollution in surface water carrying sediment, nutrients, and crop protection chemicals.

Several factors, such as surface topography, stratigraphy of geological materials, geochemical environment beneath buffers, and hydraulic properties of different units, may affect the ability of riparian buffers to remove nitrate and sediments from surface water and groundwater (Andress, 1999; Hill et al., 2000; Gold et al., 2001; Addy et al., 2002; Wineland, 2002; Simpkins et al., 2002; Spear, 2003; Chen and MacQuarrie, 2004; Hill et al., 2004; Kellogg et al., 2004; Puckett, 2004; Vidon et al., 2004; Puckett et al., 2005). Understanding the fate and transport of dissolved agricultural chemicals requires an understanding of the hydrological system (Puckett, 2004; Vidon et al., 2004; Puckett et al., 2005). The goal of this study was to investigate the regional hydrology and possible NPS sources to the Mark Twain Lake watershed using a mathematical model. Hence, the objectives of this study were to establish a conjunctive surface water and groundwater model for this area and to study the direction and amount of groundwater discharge through buffers.

There are many models that could be used to evaluate the potential effects of buffers. Models such as the Water Erosion Prediction Project (WEPP), the Soil and Water Assessment Tool (SWAT), and the Root Zone Water Quality Model (RZWQM) have been used to characterize runoff, soils, and chemical losses from claypan soils. Although their performances for these soil, crop, and climatic conditions were satisfactory, these models were not developed to simulate stream flow and water quality.

By comparison, the analytic element (AE) method needs less information and is easy to implement for large areas such as the one in this study. GFLOW is an analytic element, conjunctive surface water-groundwater model, which simulates the shallow groundwater system and its interaction with surface water features. For investigating regional hydrology, GFLOW simulation is the best suited for this study. GFLOW was applied to the northeastern Missouri, including Mark Twain Lake. The calibrated model was used to evaluate how the claypan soils affect the behavior of regional hydrology and further influence the possible setting of buffers. The parameters used in the model and hydrological results from the simulation could be informative for further research and BMP (Best Management Practices) settings.

PREVIOUS WORK

Hydrology and Hydrogeology of Riparian Buffers

Riparian buffers reduce chemicals and sediments from agricultural activity in both surface runoff and groundwater. Buffers efficiency is enhanced under conditions of long residence time and geology that confines the flow of nitrate-rich groundwater to the shallow depth beneath the buffers, where available organic carbon is plentiful and dissolved O_2 concentrations are low (Andress, 1999; Hill et al., 2000; Addy et al., 2002; Wineland, 2002; Simpkins et al., 2002; Spear, 2003; Chen and MacQuarrie, 2004; Hill et al., 2004; Kellogg et al., 2004, Cheng, 2005; Puckett et al., 2005). Hill (1996) studied the hydrogeologic settings of different sites that remove nitrates effectively and found the sites had similar hydrogeologic settings—the riparian zones had an impermeable layer below permeable surface soils and sediments. The impermeable layer produced shallow subsurface flow with long residence time and extensive contact with the vegetation roots in the buffers area. Puckett (2004) found that in some hydrogeologic settings, where tile drains and ditches drain fields or where groundwater flows beneath organic-rich, riparian sediments, groundwater flow paths may pass below reducing conditions in a riparian zone and discharge nitrate-rich groundwater directly to streams (Figure 5). That is similar to ideas presumed by Gold et al. (2001) who also showed that site attributes, such as soil wetness and geomorphology, affect the interaction of nitrate-enriched groundwater with parts of the soil ecosystem possessing elevated biogeochemical transformation rates. Riparian zones located on outwash and organic/alluvial deposits have high potential for nitrate-enriched groundwater to interact with the biological active zone. Deep limestone or sand aquifers beneath the riparian buffers may cause groundwater to bypass buffer processes and flow directly to the stream (Wineland, 2002; Simpkins et al., 2002).

McGlynn and Seibert (2003) used an elevation analysis method to evaluate "buffer capacity" by computing the watershed characteristics, such as the distribution of riparian and hillslope inputs to the stream network, the variation of riparian-area percentage along the stream network, and sub-watershed area distributions. The hydrology of riparian zones is strongly influenced by the landscape hydrogeology setting and encompasses the location of the riparian zone in the watershed in relation to surface and groundwater flows as well as the geological characteristics such as topography, stratigraphy and hydraulic properties of sediments that control hydrology (Vidon et al., 2004). Puckett and Hughes (2005) showed that coarse sediments below the riparian zone provide preferential flowpaths for nitrate in groundwater to pass beneath the chemically reducing layer and enter the stream. Groundwater influenced surface water chemistry during the low flow periods of the year. In summary from previous studies and research, both hydrology and hydrogeology are important to the effectiveness of riparian buffers.

Models Used to Evaluate Riparian Buffers

WEPP is an erosion model for simulation of runoff and soil losses for soil conservation planning, whereas, RZWQM is a one-dimensional (vertical) water-quality model for simulation of interested points within a field (Flanagan et al., 1995; Ghidey et al., 2005). The Soil and Water Assessment Tool (SWAT) has been used to simulate the hydrology and water quality within this region (Ghidey et al., 2005). SWAT is a distributed watershed model developed by USDA-ARS to assess the impacts of land use management on water, sediment, and agricultural chemical discharges from large complex watersheds with varying soil, land use, and management conditions over a long period of time. It has eight major components including hydrology, weather, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, and land management (Arnold et al., 2001; Ghidey et al., 2005). Similarly, the Riparian Ecosystem Management Model (REMM) simulates storage and movement of surface and subsurface water, sediment transport and deposition, sequestration, cycling of nutrients, and vegetative growth. For the hydrology component, REMM needs daily weather data, daily surface water and groundwater flow loading, parameters presenting the topographic and soil and vegetative conditions within riparian buffers (Inamdar et al., 1999; Altier et al., 2002). Therefore, most of the models need detailed information on parameters to perform simulations and need many parameters for a large region.

Site Description

Mark Twain Lake is a U.S. Army Corps of Engineers (USACE) reservoir located about 120 miles (200 kilometers) northwest of St. Louis (Figure 6) and has a total watershed area of over 600,000 ha (nearly 1.5 million acres). The area is used predominately for row crop farming and livestock production, and, like many other watersheds in the Midwest, agricultural nonpoint source pollution represents the primary threat to water quality and is a major concern to water resource management.

The soil, geology, and vegetation of the Mark Twain Lake sub-watersheds are similar. The majority of each watershed area is classified by the USEPA (2000) as the Central Irregular Plains Ecoregion (Level III classification), where well-developed claypan soils overlie glacial till and limestone, sandstone, and shale bedrock (Figure 7). Alfisols (MLRA

113: Aqualfs, MLRA 115: Udalfs) are the dominant soil order of the region (Figure 3; Figure 8), and much of the upland soils are developed from loamy till and loess deposits. The soils developed on upland are aqualfs, for example, Mexico soil and Putnam soil (Figure 8). Wetness and erosion limitations are the primary concerns in soil management for agricultural use. Elevation ranges from 200 to 300 m (650 to 1000 ft) above mean sea level. It consists of nearly level to gently sloping silt-mantled plains. Average annual precipitation of the area is about 1025 mm (40.35 in). Approximately 60 percent of the precipitation falls during the freeze-free period.

In 2002, the Agroeology Issue Team of the Leopold Center for Sustainable Agriculture at Iowa State University instrumented a Riparian Management System (RiMS) in Crooked Creek watershed with 12 wells that were monitored monthly (Figure 9). The RiMS is a management approach for environmental enhancement of intensively modified agricultural landscapes mostly in the Midwest of U.S., and has been found to successfully control NPS contamination in many studies (Puckett, 2004; Schultz et al., 2004; Puckett and Hughes, 2005). The team collaborated with the Center of Agroforestry at the University of Missouri, to extend successful buffers experiences from Iowa to Missouri. The Crooked Creek site was designed to investigate the effectiveness of different riparian buffer setting (Figure 10). Typical buffers settings with woody-nonwoody zones occur on the northern shore of the creek and pasture occurs on the southern shore. Monitoring well nests A, B, and C were installed on the buffer side of the creek and well nests D, E, and F were installed on the pasture side. Each nest consists of two wells at different depths. The well screens of the shallow wells of these nests are located in alluvial materials of sand and gravel, whereas, the well screens of the deeper wells are located in the limestone bedrock (Figure 11). The water table can usually be found in the uppermost wells at each site and is about 207 m. Well A10 is located between grass zone and crop field and is usually dry during the dry season. Hydraulic head values from well nests at the site indicate that groundwater flows towards the creek on both the pasture side and the buffer side. Hence, Crooked Creek in the study reach is a gaining stream. Otter Creek and Long Branch are the interested sub-watersheds in the area (Figure 12).

Hydrogeological Setting

Bedrock in northeastern Missouri is composed of rocks of Mississippian System, represented by ten Formations. The uppermost of the Mississippian limestone layer, Ste. Genevieve Limestone (Chesterian Series), underlies the Pre-Illinoian loess and till (Thompson, 1995). According to the Ground Water Atlas (USGS, 1997), there are 7 principal aquifers at the land surface in the area. The main aquifer systems of the study area are the surficial aquifer and the Mississippian aquifer system (Figure 13, Figure 14). The surficial aquifer system primarily consists of unconsolidated deposits of late Quaternary age. The materials are sand and gravel from stream deposits (stream-valley aquifer) and glacial-drift deposits (glacial-drift aquifer). The stream-valley aquifers consist mostly of sand and gravel of the Holocene Age, but locally include sediments of the Pleistocene Age. The average thickness of the aquifers is about 30 m (90 to 100 ft), but locally they are as much as 50 m (160 ft) thick. The thickness of the glacial drift generally is 30 to 60 m (100 to 200 ft), but locally is greater than 90 m (300 ft) in eastern Missouri.

The Mississippian aquifer in northeastern Missouri (Figure 15) consists of carbonate rocks (Ste. Genevieve Limestone, Chesterian Series) that are stratigraphically equivalent to those that compose the uppermost aquifer of the Ozark Plateaus aquifer system. The thickness of the Mississippian aquifer averages about 60 m (200 ft), but locally exceeds 120 m (400 ft) in northwestern Missouri. In most places, the aquifer is overlain by a confining unit of Pennsylvanian shale and sandstone, and is everywhere underlain by a confining unit of Mississippian shale (USGS, 1997).

A claypan is defined as a dense, compact layer in the subsoil having high clay content (Kelly and Pomes, 1997). A characteristic claypan soil has an argillic horizon about 20 to 40 cm deep and clay contents of more than 450 g/kg. The principal clay mineral of the claypan is montmorillonite, which is subject to large changes in volume with changes of moisture content. Because of the argillic horizon, claypan soils may perch water and create lateral flow. Claypan soils and local hydrology have been studied within the Mark Twain watershed or the contiguous areas. The consensus view is that infiltration is small and runoff (overland flow) dominates (Hjelmfelt and Wang, 1999; Blanchard and Lerch, 2000; Lerch and Blanchard, 2003; Udawatta et al., 2004; Seobi et al., 2005). Blanco-Canqui et al. (2002) evaluated saturated hydraulic conductivity (K) and its impact on simulated runoff for claypan soils. They suggested that surface runoff accounts for about 85 percent of the mean annual streamflow due to the behavior of the claypan in the region, a value similar to that is given by Hjelmfelt and Wang (1999). At the Greenley Memorial Research Center, Udawatta et al. (2004) conducted a study on phosphorus loss in three adjacent watersheds with claypan soils. They found that claypan soils are capable of producing runoff volumes of greater than 75 percent of the precipitation, depending on antecedent soil moisture, and producing a 64 to 73 percent loss of total phosphorus. Similar results were obtained in another study at the MSEA (Missouri Management System Evaluation Area) site in Goodwater Creek (Tindall and

Vencill, 1995). Preferential flow was the dominant mechanism of recharge and transport of agricultural chemicals to groundwater through a claypan (Tindall and Vencill, 1995; Kelly and Pomes, 1998). Hjelmfelt and Wang (1999) simulated the hydrologic response of grassed waterways in Goodwater Creek watershed and found that grassed waterways retard overland flow and reduce the energy for soil erosion and transport in claypan soils. Infiltration is a significant mechanism for herbicide leaching to groundwater in these instances.

METHODS

Analytic Element Modeling

Compared to well-known finite-difference techniques, the application of the analytic element (AE) method is a relatively new method in surface water and groundwater modeling. AE models have demonstrated their capability to address complex hydrogeologic and natural resource issues in a relatively simple manner and have become increasingly popular especially in studies of groundwater/lake interaction (Hunt and Krohelski, 1996; Hunt et al., 1998; Dunning et al., 2002; Hunt et al., 2003; Simpkins, 2006; Hunt, 2006). In contrast to strictly numerical techniques, such as finite-difference (MODFLOW) or finite-element (SUTRA; MODFE) models, the AE method does not require a grid structure and assumes infinite aquifer extent (Dunning et al., 2002). Features important to groundwater flow (for example, wells) and surface water features (for example, streams, ponds, and lakes) are entered as elements or strings of elements. Each element is represented by an analytical solution. By calculating the solution for every element in the groundwater flow system, the model provides a hydraulic head estimate at every point for the entire model domain instead of nodal interpolation between cells (Hunt and Krohelski, 1996; Dunning et al., 2002; Fowle, 2003; Hunt et al., 2003).

The analytic element model, GFLOW version 2.1.0 (released in July 2005), was used to simulate the groundwater and surface water system for Mark Twain Lake in northeastern Missouri. GFLOW is a two-dimensional, single-layer, steady-state simulation founded upon the Dupuit-Forcheimer assumption of horizontal flow (Strack, 1989; Haitjema, 1995). The Dupuit-Forcheimer approximation assumes groundwater flow in the singly layer is horizontal and is valid when the aquifer is thin relative to its extent. GFLOW uses natural hydrologic boundaries present in the model domain instead of discrete boundaries specified by the model user, like MODFLOW. During simulation, GFLOW uses the superposition of elements, which represent hydrogeologic features and surface water boundaries, to model groundwater flow in a region. The elements may include wells, linesinks (rivers and streams), and inhomogeneities (areas with differing base elevation, hydraulic conductivity, porosity, or recharge values).

The model is considered a simplified representation of the natural hydrologic system because it contains a single value of hydraulic conductivity and a single, uniform recharge rate over the entire model domain (Hunt and Krohelski, 1996). GFLOW allows for the representation of large domains that include many hydrologic features outside the immediate area of interest. Furthermore, GFLOW also has the ability to simulate interaction between surface water and groundwater, and is easily modified by adding additional hydrologic features (Hunt et al., 1998). The Mark Twain Lake represents the main hydrologic feature in this region and can be used in the model for assuring the estimation of groundwater and surface water interaction. The new AE lake package is based on an enhancement of stream networks with steady-state streamflow calculation. A steady-state simulation of lakes with both groundwater and surface water inflows and outflows and an initially unknown lake stage are included in this version of GFLOW. It allows the model to estimate the changes of regional relationships to stream flow, groundwater, and lake in the model domain (Simpkins et al., 2001; Hunt et al., 2003; Simpkins, 2006). The lake can stand alone or be part of a stream network, including surface water inflow from streams upgradient and outflow through an outlet stream. The outflow depends on the lake stage, and is calculated using a linear interpolation between a lake stage table and stream outflow rate at that stage (Hunt et al., 2003; Simpkins, 2006). The model calculates a lake stage iteratively, based on ground and surface water inflow and outflow, precipitation, and evaporation using the secant method (Hunt et al., 2003). In this method, the user specifies a lower and an upper estimate of the lake stage, φ_1 and φ_2 ,based on prior data, respectively. A conjunctive groundwater and surface water solution is generated for each lake stage, which produces values of ΔQ_1 and ΔQ_2 known as the water balance "deficiency" and given by:

$$\Delta Q = \sum \alpha^i + l^i + \sum Q_0^i + \sum Q_{in} - \sum Q_{out} + A(\varphi)E$$

where α^i is the sink density of the *i*th linesink, l^i is the length of the *i*th linesink, Q_0^i is the overland flow into the *i*th linesink, and $\sum Q_{in}$ and $\sum Q_{out}$ are the contributions from inlet streams to the lake and discharge from the lake into outlet streams, respectively. The last term $A(\varphi)E$ is the product of the lake area (which depends on stage) and the net precipitation rate (precipitation rate minus evapotranspiration rate). A new lake stage, φ, is calculated using the equation

$$\varphi = \varphi_1 - \frac{(\varphi_2 - \varphi_1)\Delta Q_1}{\Delta Q_2 - \Delta Q_1}$$

and the process is repeated and values reentered into the equation until a lake stage solution is attained. The number of iterations is controlled by the user, and the water balance can be checked manually (Hunt et al., 2003; Simpkins, 2006).

Particle tracking is also implemented in GFLOW. The distance and path lines are internally calculated in the domain by multiplying the specified time by the groundwater velocity in GFLOW. In general, particle tracking is used to trace flow paths by following infinitely small, imaginary particles through the flow field, especially, the groundwater flow and pollution problems, which can not be easily seen and treated like surface water. This technique is good for visualizing the overall flow field (areas of influence) and tracking contaminant paths underground (Anderson and Woessner, 1992). After the model is calibrated, assigned particles in the model domain can represent the possible contaminants flow path and source area.

Hydraulic Parameters

Although the claypan soils cover about 4 million ha of the land surface in the Midwest section of the U.S., published data for K values for claypan soils as well as alluvial sediments and sandstone/limestone aquifers are limited (Blanco-Canqui et al., 2002). Information on field K values in horizons above the claypan is also important for determining lateral flow and for assessing runoff and erosion, and groundwater contamination simulations. Kelly and Pomes (1998) studied undisturbed cores from the MSEA (Management System Evaluation Areas) site in Goodwater Creek Basin near Centralia, Missouri and produced laboratory K values ranging from 5.36×10^{-5} m/day (2.03×10^{-9} ft/s) to 6.48 m/day (2.46×10^{-4} ft/s). Baer and Anderson (1995) showed K values from 0.03 m/day (1.14×10^{-6} ft/s) to 0.16 m/day (6.07×10^{-6} ft/s). Column studies by Tindall and Vencill (1995) showed K values ranging from 0.13 m/day (4.93×10^{-6} ft/s) to 0.30 m/day (1.14×10^{-5} ft/s). Values for the claypan matrix were three to four orders of magnitude less. Blanco-Canqui et al. (2002) measured field and laboratory K values for various depths in the Midwest Research Claypan Farm (McCredie) near Kingdom City, Missouri. During his evaluation of the water erosion prediction project (WEPP), the effective K with bentonite (0.03 m/day, 1.14×10^{-6} ft/s, 1.3 mm/h) and without bentonite (0.08 m/day, 3.04×10^{-6} ft/s, 3.4 mm/h) from McCredie, Missouri and also the effective K without bentonite (4.41 m/day, 1.67×10^{-4} ft/s, 183.6 mm/h) from Novelty, Missouri were employed as the model input in his study (Table 1). The values above were all in claypan soil.

Slug tests were performed in summer 2005 in monitoring wells on both sides of the Crooked Creek site. Hydraulic conductivities were obtained using the Bouwer-Rice solution with unconfined aquifers and the data were analyzed using AQTESOLV (V3.1) software (Figure 16) (Bouwer et al., 1976; Fetter, 2001; Schwartz et al., 2002). Both falling head and rising head slug tests were performed and produced K values ranging from 3×10^{-3} m/day (1.2×10^{-7} ft/s) to 1.9 m/day (7.2×10^{-5} ft/s) for the wells within the alluvium and also limestone bedrock (Table 2).

The water table for six well nests, including 12 monitoring wells in Crooked Creek site, was monitored monthly since 2002. Well nest A, B and C are located at the buffer site; nest D, E and F are located at the pasture site (Figure 9). Hydraulic heads for each well from April 2002 to April 2005 (Figure 17) were used in simulation as calibration targets. Head values were averaged to show the long-term, steady-state condition. Before the average data could be used for simulation, the hydraulic heads needed to be corrected to absolute elevation (above mean sea level). A licensed surveyor was employed to survey the top elevation of the 12 monitoring wells at the Crooked Creek site. The water table for each well nest usually can be found between two wells at different depth. The upper head value probably is the best representation of the water table. Six head calibration targets were add to the model representing hydraulic heads of well nest A to F (Table 3).

Model Construction

Base maps for the model domain were imported to GFLOW as GIS files shape files (a new feature of GFLOW). Binary base maps (BBM files) of the model domain were first obtained from the United States Environmental Protection Agency's website (Figure 18). The binary base maps of roads and hydrology were downloaded and used to create a database in GFLOW; however, the format is not flexible. Moreover, previous methods of interpreting linesink elevations from topographic maps could be inaccurate. A new way of creating the base maps and interpreting linesink elevations in ArcMap is outlined below.

The model domain was defined by centering on the Mark Twain Lake and generating a focus area of the model, which includes major parts of four major streams in the region, including smaller reaches such as the North Fork, Middle Fork, Elk Fork and South Fork of the Salt River, Long Branch Creek, Crooked Creek and Lick Creek (Figure 19). The constructed near-field region results in a 3,000 km^2 area (300,000 hectares) in the center of the model with an entire domain representing approximately 6,000 km^2 (600,000 hectares) in northeastern Missouri (Figure 20). A larger domain was developed to ensure the inclusion of all significant hydrologic boundaries, which may influence the Mark Twain Lake watershed. Linesink elements, which represent stream segments in the model domain, were drawn over the base maps by entering their starting and ending hydraulic heads. The elevation base map of major river intersection points was produced from DEM (Digital Elevation Model, data are from Missouri Spatial Data Information Service) data with an ArcView script named "givemepoint" (Appendix B). The script was downloaded from the support section of ESRI website (http://arcscripts.esri.com/details.asp?dbid=13300). By combining the elevation base map and major rivers map from GIS into GFLOW, the assigned starting and ending elevations of streams is probably more accurate than reading from a regional topographic map with elevation contours (Figure 21).

GFLOW requires the width, depth, and estimated resistance of each stream segment to be entered into the model. The depth is specified as "…the approximate distance between the surface water elevation in the stream and the bottom of the resistance layer underneath the stream" (Haitjema, 1995; Haitjema, 2005-GFLOW Help). The resistance parameter is defined as "…the thickness of the low permeable layer underneath the stream divided by its vertical hydraulic conductivity" (Haitjema, 1995; Haitjema, 2005-GFLOW Help). In essence, it represents the time it takes water to flow through the streambed, due to the presence of a layer, consisting of tightly packed, fine-grained particles. The width and depth of the segments were determined by trial-and-error during the procedure. Other width parameters of near-field element linesinks with unassigned values were estimated in the calculation (another new function of this version of GFLOW). Those parameters were assigned referring to the values from previous models (Hunt et al., 2000; Fowle, 2003; Hunt et al., 2003; Simpkins, 2006) (Table 4). The width parameter of the lake linesink represents the leakage zone near the lake perimeter (Hunt et al., 2003).

A shape file consisting of a base map of the surficial geology of the State of Missouri was also obtained from the Missouri Spatial Database Information Service (http://msdisweb.missouri.edu/index.htm) (Figure 22). The shape file was overlain on the GFLOW model to identify possible inhomogeneities for alluvial deposits in the model domain. Subsequently, ten inhomogeneities were defined in the model along the rivers within the Mark Twain Lake watershed. Compared to the global K of the model, these alluvial channel deposits were assigned with K values of 100 m/day, which are about 2 orders of magnitude higher than the K value of aquifer estimated by slug tests in those units (Hunt et al., 2000; Fowle, 2003; discussion with Simpkins).

The K value of the model was initially set at 2 m/day (7.6×10^{-5} ft/s), which is one order higher than the results estimated by the slug tests and previous research around this area (Table 1, Table 2). The model K value obtained using field methods should represent the average K of a larger thickness unit, which includes the effect of loess, sand, gravel in the main aquifer and claypan soil layer (Fetter, 1999; Fowle, 2003). The scale effects represent the greater distance over which the parameter is measured, the greater value of the parameter is observed (Bradbury and Muldoon, 1990). This larger value was used as result of the scale dependence of hydraulic conductivity and also possible for preferential flow (Kelly and Pomes, 1998; Tindall and Vencill, 1995).

Model input parameters include a base elevation of 125 m (409.8 ft) above sea level and an aquifer thickness of 200 m (655.7 ft). The value of the aquifer's thickness controls the saturated height that groundwater can rise above the base elevation. Consequently, it is assigned a large value to allow the saturated thickness to fluctuate and ensure that unconfined conditions are present for model simulations. Model porosity of 0.10 to account for claypan soils, inhomogeneity porosity of 0.25 (the characteristic value for sand, Freeze and Cherry , 1979), and resistance of 0 days were also initially specified for the near-field linesinks in the model (Table 4). Resistance values are not well documented. Previous modeling experiences in assigning resistances in different studies were considered (Hunt et al., 2000;

Fowle, 2003; Hunt et al., 2003; Simpkins, 2006). The resistance values were estimated by adjusting values manually based on previous research. Hunt et al. (2000) used resistance values of 0.3 to 2 days in his model for Genesee Lake in Wisconsin and 0.3 days for other linesinks. Resistance of 7.5 days was used in his lake simulator comparison (Hunt et al., 2003). A mean lake level of 184.92 m (606.3 ft) was used in the model (Figure 23). This value represents the average level of the Mark Twain Lake from April 2002 to April 2005 using records from USACE (St. Louis office).

For initial simulations, areal recharge over the entire model domain was specified as 0.000279 m/day (4.0 in/yr, 10 percent of the mean annual precipitation of in the region) (http://www7.ncdc.noaa.gov/IPS/CDPubs?action=getstate#PERIOD_OF_RECORD). After complete model construction, the GFLOW model consisted of approximately 1150 equations that were solved simultaneously when the program was run. This included about 630 linesinks and 250 inhomogeneity elements.

Baseflow Separation

Baseflow is considered the component contributed from groundwater to a stream or river. Hydrograph separation is the method usually used to estimate baseflow. In order to calibrate the GFLOW model which calculates baseflow, the discharge due to baseflow was calculated using the Baseflow Index (BFI) (version 4.12w) (Wahl and Wahl, 1995) (www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/). BFI was developed using the Institute of Hydrology procedures that were developed in 1980 (Wahl and Wahl, 1995). The baseflow index is the total volume of base flow divided by the total volume of runoff for a period (Wahl and Wahl, 1995). Stream discharge data from five USGS gauging stations were used for discharge calibration in the model (Figure 24). The computer program provides an automated method of determining the ratio of baseflow to total flow volume for a given year(s) by using local minimum analysis with a recession-slope test (Wahl and Wahl, 1995; Fowle, 2003). Stream discharge records for the program were obtained from the USGS National Water Information System (NWIS) website (http://waterdata.usgs.gov/nwis/).

In the BFI procedure, the Institute of Hydrology (Standard Method) baseflow separation method was used with the default value of the turning point test parameter (f = 0.9) for each value of N (turning point) between 1 and 10 days. When the baseflow index is plotted versus the N value, the point at which slope changes in the graph indicates the value of N that should be used to evaluate baseflow (Figure 25). Although the method may not be as accurate as more sophisticated techniques, previous work has shown that the output is consistent and indicative of long-term baseflow trends (Wahl and Wahl, 1995).

The baseflow index value computed by the BFI program was used to calculate the stream discharge, due to baseflow (Table 5). The resulting discharge value was then compared to model simulations, which include only baseflow. The stream discharge (flux) due to baseflow for five USGS gauging stations in the area were entered into the model as flux calibration targets and used for model calibration. These five gauging stations were located at the Salt River, Crooked Creek, Middle Fork and Elk Fork of Salt River, and Lick Creek. Approximate locations of the stream gauging measurements and accompanying data are shown in Table 6.

Model Calibration

Model calibration utilized nearly three years of existing hydraulic head data (2002 to 2005) from 12 monitoring wells located at the Crooked Creek site. The mean observed heads were calculated and inserted as head test points. Four lake stage test points were added along the lake element boundary to insure the accuracy of the lake stage during simulation. Five flux targets (from baseflow separation) were also inserted into the near-field area. After entering these three different types of test points, trial-and-error calibration ensued. The differences between modeled and observed heads at Crooked Creek site were used as indicators of the model fit.

An optimal set of parameters that best fits observed and modeled data was determined, using the parameter estimation technique program UCODE (A Computer Code for Universal Inverse Modeling) (Hill, 1998). The use of parameter estimation for calibration of groundwater models is a relatively new technique (Hunt et al., 2000). The program UCODE automatically calculates parameter values, such as hydraulic conductivity and recharge, which are a "best fit" between user-provided observed data (hydraulic head and streamflow) and simulated model output. In UCODE, the nonlinear regression problem is solved by minimizing a weighted least squares objective function with respect to the parameter values using a modified Gauss-Newton method. In addition, UCODE output includes statistics that indicate the significance of the model calibration, such as parameter sensitivities and correlations. These statistics are to: (1) identify inadequate data and parameters that may be difficult to estimate, (2) evaluate estimated parameter values, (3) evaluate the model representation of actual processes, and (4) quantify the uncertainty of model simulated values (Poeter and Hill, 1998).

UCODE is integrated within this version of GFLOW through the graphic user interface (GUI). First, the weights for different targets are assigned. Then, the five main input files are produced automatically by a UCODE GUI window. This includes the universal (*.uni), preparation (*.pre), and extract files (*.ext) (one of each is needed for each UCODE run), the function file (*.fnc) (optional, one may be used for each UCODE run), and template files (*.tpl) (one or more are used for each UCODE run) (Poeter and Hill, 1998). The settings for these input files can be later modified by the needs of user in a text editor prior to running the PERL code.

The UCODE calibration was optimized through the use of three types of calibration targets (6 head test points, 5 baseflow discharge points, and 4 lake stages) (Table 7). Targets with higher uncertainty (higher standard deviations) were given lower weights for calibration. UCODE assigned the weights ($1 / \alpha^2$) using the standard deviation entered for each observation. Furthermore, the weighting assignments were based on several GFLOW modeling studies (Hunt et al., 2000; Hunt et al., 2003; Fowle, 2003; Simpkins, 2006). A tolerance convergence criterion (TOL) was defined as 0.01. Detail parameter settings from a universal file are as shown in Appendix C.

Phase 1 was run to ensure correct program processing. Errors in the input code were detected during this stage and corrected before the next phase of calibration was executed. Next, Phase 22 was executed to calculated parameter sensitivities, variances, and correlations. The differences between perturbed simulated values and the unperturbed simulated values are used to calculate forward-difference sensitivities (Poeter and Hill, 1998). The purpose of sensitivity analysis is to quantify the uncertainty of the calibrated model introduced by the uncertainty of the estimated hydraulic parameters, recharge, and boundary conditions

(Anderson and Woessner, 1992). The sensitivities of the simulated values to the parameters are expressed as:

$$ss_{ij} = \left(\frac{\partial y_i'}{\partial b_j}\right) b_j \omega_{ii}^{1/2}$$

where, *ssij* is the scaled sensitivity; *yi'* is the simulated value which corresponds to the *i*th observation; *bj* is the *j*th estimated parameter; $\frac{\partial y_i'}{\partial b_j}$ is the sensitivity of the simulated value with respect to the *j*th parameter and evaluated at b; *b* is a vector containing the parameter values at which the sensitivities are evaluated; ω_{ii} is the weight of the *i*th observation. (Hill, 1998).

In order to indicate the sensitivity for the estimation of each parameter, composite scaled sensitivities are calculated by using the scaled sensitivities for all observations. The composite scaled sensitivity for the *j*th parameter, css_j, is expressed as

$$css_j = \left[\sum_{i=1}^{ND} (ss_{ij})^2 \big|_b / ND\right]^{1/2}$$

where *ND* is the number of observations being used in the regression and the quantity in parentheses equals the scaled sensitivities (Hill, 1998).

If there is a large change in the model solution due to a small change in a parameter value, the parameter is assigned a large composite scaled sensitivity. Dimensionless composite parameter sensitivities are used to indicate the total amount of information provided by the observations for the estimation of the parameter values (Hill, 1998).

After composite scaled sensitivities were calculated and significant parameters were estimated through Phase 22, Phase 3 was executed to obtain the final optimal parameters. During this phase, UCODE calculated the optimal parameters with the lowest sum of squared weighted residuals. The weighted least-squares objective function S (b) used in UCODE can be expressed as:

$$S(b) = \sum_{i=1}^{ND} \omega_i \left[y_i - y_i'(b) \right]^2 + \sum_{p=1}^{NPR} \omega_p \left[P_p - P_p'(b) \right]^2$$

where b is a vector containing values of each of the NP parameters being estimated; *ND* is the number of observations; *NPR* is the number of prior information values; *NP* is the number of estimated parameters; *yi* is the *i*th observation being matched by the regression; *yi'(b)* is the simulated value which corresponds to the *i*th observation; *Pp* is the *p*th prior estimate included in the regression; *Pp'(b)* is the pth simulated value; ω_i is the weight for the *i*th observation; ω_p is the weight for the *p*th prior estimate (Hill, 1998).

This function is calculated by subtracting the simulated values from the observations and weighing, squaring, and finally summing the residuals. UCODE adjusts the value of the specified input parameters in an iterative procedure to minimize the value of the weighted least-squares objective function. The change in parameter values is then compared to convergence criteria. If the change is too large and the maximum number of specified iterations (two times the number of parameters) has not been reached, the next iteration is executed (Poeter and Hill, 1998). If the change is small, the parameter estimation converges and the final estimated parameter values are reported (Figure 26). In addition, calculated statistics are printed to an output file (Appendix D). Depending upon the size of the model, Phase 3 can take between one to four hours or even one day to converge on an optimal solution. For instance, the run of Phase 3 in this study took about nine hours to converge.

Residuals and sensitivities are used to perform parameter-estimation iteration. The last step of parameter-estimation iteration is to compare the two quantities, the changes in the parameter values and the change in the sum-of-squared-weighted residuals against convergence criteria (Poeter and Hill, 1998). The parameter values are assumed to be the optimal parameter values until the changes are small enough and parameter estimation converges. These values have produced the best possible match between the simulated and observed data obtained from the weighted least-squares objective function (Poeter and Hill, 1998). When the calibration process and sensitivity analysis are complete and the optimal hydraulic parameters are determined, the calibrated model can be used to evaluate the hydrological characteristics of the simulation domain.

After parameters were estimated by UCODE, another parameter estimation program PEST (Model-Independent Parameter Estimation; Doherty, 2004), was run to determine additional optimal sets of parameters. PEST uses the Gauss-Marquardt-Levenberg method of nonlinear parameter estimation that decreases the discrepancies between observations and simulated values to a minimum in weighted least squares (Doherty, 2004). Similar to UCODE, PEST is also integrated into this version of GFLOW and can be modified within the GUI window. PEST requires three types of input files—template files, instruction files, and a PEST control file. It also provides PEST with the model name, initial parameter estimates, field or laboratory measurements to which the model outcomes must be matched, prior parameter information, and a number of PEST variables which control the implementation of the Gauss-Marquardt-Levenberg method (Doherty, 2004).

Before PEST was executed, the minimum and maximum values of K for each model zone and recharge rate were specified. The objective function criterion was defined as 0.01 (Appendix E). Unlike UCODE simulation, no parameters were removed in the PEST calibration. PEST was executed to determine another optimal set of parameters and to calculate the correlation coefficients among these parameters. Presumably, if the two parameter estimation programs produced the same calibration results, the parameters would be optimal parameters for this model. Further research would be needed to determine which set was more reasonable for this model. The results from different parameter estimation methods in this study would be informative for future modeler choices.

RESULTS AND DISCUSSION

Baseflow Separation

Results from the BFI program show that the baseflow is lower than central Iowa and other regions (Tony Wahl, written communication, 2005) (Table 5). Fowle (2003) documented that the BFI value of South Skunk River gauging station in her model was 0.446 indicating that about 50 percent of the stream flow is contributed by the groundwater. In contrast, the BFI values from the Mark Twain Lake watershed are about 0.09. The low BFI value shows that there is less interaction between the surface water and groundwater system as a result-not much groundwater inflow to streams during the analysis period. This phenomenon corresponds to the effect of less permeable materials within the region, which are the claypan soils. The same phenomenon, which indicated the difficulties of infiltration and the abundant surface runoff, was suggested from several previous studies in the vicinity area of the Mark Twain Lake watershed, such as the Goodwater Creek basin in northeast Missouri (Hjelmfelt and Wang, 1999; Blanchard and Lerch, 2000; Lerch and Blanchard, 2003; Odawatta et al., 2004; Seobi et al., 2005). Most of the precipitation in the Mark Twain Watershed is routed though overland flow into streams.

Model Calibration

The groundwater flow model was run under steady-state conditions using the initial K values of 2 m/day and the recharge rate of 0.000279 m/day (10 percent of mean annual precipitation). After the first run, because the sum of squared differences were very large between values of the observed targets and those simulated in the model, calibration by trial-and-error was initiated. Based on the range of K and possible effects of the claypan soil, the K was adjusted to 5 m/day and R was reduced to 0.000195 m/day (7 percent of mean annual precipitation). The width and resistance of linesinks in the model were the only components that were adjusted during this process. The manual calibration results and statistics regression are as shown (Figure 27, Table 8).

Afterwards, automatic calibration methods were employed to determine the best fit of the model parameters. UCODE originally ran with 12 parameters (model K, model R and 10 K values for alluvium inhomogeneities) and produced the composite-scaled sensitivities (phase 22) that indicated that the model calibration was most sensitive to model K, model recharge, and K for alluvium inhomogeneity at Crooked Creek (composite scaled sensitivities: K=2.71, R=4.61, $K_{crooked}$=5.09, others=0.052, 0.45, 1.90, 1.69, 1.30, 1.46, 0.024, 0.05, and 0.39). The model was relatively insensitive to changes in K values of the other alluvium inhomogeneities. These K values were omitted during phase 3.

Overall, calibration statistics showed a good match between observed flux and simulated flux (Figure 28). The same trend and relationship was found for the observed head and simulated head (Figure 29). However, the observed head and simulated head did not fit a regression line as well due to the small values (less than 0.5 m). The root-mean-squares (RMS) difference and sum of squared differences for the head values were 1.0 and 5.9 respectively. However, the RMS difference and sum of squared differences for flux values were 1,668 and 13,900,000 m^3/day, respectively. This apparently large value might be because of the unit conversion between cfs (cubic feet per second) and m^3/day. After converting to cfs, the RMS difference and sum of squared differences for flux were 0.69 and 5,670 cfs, respectively. Although these flux values still seem large, this would not affect the results of the model calibration since the modeled flux and observed flux actually match well on the regression line.

The PEST seemed to work better than UCODE by comparison. PEST ran and calibrated with all 12 parameters and 15 calibration targets (Appendix F). The parameters changed only slightly after the run and are listed in Table 8. In contrast, UCODE calculations were quite time-consuming. It took up to 9 hours to a few days to complete only phase 3 iterations and often the data did not converge. There were only 3 parameters calibrated in the end. UCODE did not respond well to the model with its many parameters and complicated settings because of its strict parameter estimation procedure. PEST did a better job calibrating and estimating all 12 original parameters for this model with less time.

Additional flux targets caused problems in convergence for UCODE. Fowle (2003) calibrated her model using only one flux target from 37 targets. Hunt et al. (2003) employed 21 head values and 1 stream discharge for UCODE calibration. For both UCODE and PEST calibration, Cheng (2005) used 11 head targets and no flux targets. However, Simpkins (2006) successfully used 6 flux targets out of a total of 31 calibration targets for a simulation of Clear Lake in Iowa. It seems that the UCODE procedure tried harder than PEST to achieve the most unique solution using both flux and head targets. On the other hand, PEST wasn't as strict as UCODE on using both types of targets. In this particular study, a concentration of head targets and too few calibration targets seemed to complicate the estimation of the parameters in UCODE. Thus, UCODE might produce more precise estimations of parameters in the end; whereas it might fail to estimate parameters of all due to an insufficient number of non-well distributed targets. PEST seems to tolerate clumped targets; however, the estimation produced by PEST might be too general for the modeling domain. This result needs to be further studied. Adding head and flux targets in wells in another watershed might help figure out the cause of this phenomenon.

Model Results

The GFLOW simulation produced equipotential lines (water-table contours), set at 10 m (~30 ft) intervals (Figure 30). This allowed evaluation of hydrologic characteristics of the Mark Twain Watershed area, such as the direction of flow in the buffered areas and the flow path of groundwater in three main sub-watersheds in the project.

By studying the orientation of the water table contours and their positions relative to the streams, several interesting features of the system were noted. Overall, groundwater flow, is generally towards the streams in the region and the streams are gaining (Figure 31). Most of the groundwater flow into the streams in the model domain was due to the high K values of the alluvium deposits along the streams, which allowed equipotentials to bend toward streams (Figure 31). However, this phenomenon does not occur in some stream branches, such as the upper part of Otter Creek. This could be more like a flow-through type of stream (Fowle, 2003). Most of the groundwater flow through Otter Creek and get into the larger catchment area of Middle Fork Salt River. This phenomenon should be further investigated in subsequent studies to more accurately characterize the groundwater system in these locations.

Backward particle tracking in GFLOW was performed to determine the flowpath of groundwater in the Crooked Creek and Otter Creek watersheds (Long Branch Creek was not constructed in the near-field area due to its orientation and consideration of the size of model domain). Generally, backward particle tracking is more suitable than forward particle tracking for delineating the possible source areas and the groundwatershed boundary. However, due to the differences of K values for the model and alluvial materials, using forward particle tracking is easier to achieve the goal of finding the groundwater watershed boundary and source area.

Particles representing pollutants were placed at the top of the model and tracked forwards 1000 years to delineate the ground-watershed boundary of Crooked Creek and Otter Creek (Figure 32a). In addition, the potential source areas of nutrients and chemicals for these two target watersheds were determined by tracking particle backward 50 years, the approximate time span which nutrients have been applied to fields in the region (Figure 32b). It is apparent that groundwater is flowing downstream within the alluvial deposits when the model is examined on a local scale near the riparian management sites. If the pollutants in the groundwater system flow into the stream with the baseflow, the resistance time within buffer will decrease and traveling time to reach the lake will reduce (the acceleration of pollutant transportation) (Figure 33). Potential riparian buffer sites in this part of Missouri might have to be perpendicular to stream to increase the contact time of contaminants with buffers in the alluvium. Further speaking, the longer of the buffers locating (parallel length) above alluvial channel will help the denitritification process of the groundwater because the contact time of pollutants and buffer is longer.

For surface runoff, topography and the existence of claypan layer are the main factors for buffers. Riparian buffers must enhance the capture of contaminants along the creek and be perpendicular to the flow path of surface runoff to trap sediments and slow runoff. Additionally, the setting of buffers for this region should reduce the impact of surface runoff in order to achieve the goal of improving water quality in the streams and also the reservoir.

For example, increasing the width of the non-woody zone or changing the species of the grass filter zone would be suitable. Further detail will be provided later in the summary section.

The specific discharge (m/day) and flux (m^3/day, volumetric flow rate) were evaluated in the model. The two terms are related by the cross-sectional area (m^2). Flux inspection lines are lines drawn in GFLOW perpendicular to the direction of groundwater flow. Flux inspection lines have an orientation—the first point entered is the starting point, marked with a small diamond. A positive flux implies water flowing from left to right across the line, when viewed from the starting point (Haitjema, 2005-GFLOW help). After a simulation, discharge across the line is calculated, reflecting the groundwater discharge throughout the entire thickness of the model.

Two sets of flux inspector lines were assigned on both sides of the Crooked Creek site in the model (Figure 34). Each set contained two flux inspector lines perpendicular to each other and centering on the well nest. The inspector line parallel to the nest had a larger amount of groundwater flowing through, at whereas the line perpendicular to the nests orientation (groundwater flowing toward stream) had a lesser amount of groundwater flowing through it. The same trend was found at both well nests. Calculated groundwater flux at the buffers site (north) was 200 m^3/day downstream, and 940 m^3/day toward the stream. Respectively, calculated groundwater flux at the pasture site (south) was 600 m^3/day toward the stream and 1750 m^3/day flowing downstream within the alluvial deposits.

Modeled groundwater discharge values can be combined with pollutant concentrations to estimate the amount of contaminants flowing through the site. Based on the advective transport concept, the one-dimensional mass flux, due to advection, is equal to the quantity of water flowing times the concentration of dissolved solids (Fetter, 1999):

$$F_x = v_x n_e C$$

F_x is mass flux (g/day-m^2)

v_x is average linear velocity (m/day)

n_e is effective porosity

C is concentration (g/m^3 or mg/L)

The observed nitrate concentration in the Crooked Creek site for the year 2002 was about 6 mg/L on the buffers side (north) and 0.3 mg/L on the pasture side (south), respectively. Assuming an effective porosity of 0.25, and a buffer width of 30 m (~100 ft) with a depth of 10 m (~32 ft) and the assumption of constant concentration in depth for the buffer side, the estimated nitrate load flowing through the site were 90 g/day toward the stream and 423 g/day toward downstream under the same cross-sectional area. For the pasture side, the nitrate loadings were 270 g/day toward stream and 788 g/day toward downstream.

The water supply of northeastern Missouri was examined using the Mark Twain Lake water balance. After calibration, the discrepancy of lake water balance was 0.0068 percent. The lake received about ten times more groundwater inflow (101,000 m^3/day, 11 percent) than outflow (18,000 m^3/day, 2 percent) (Table 9). Sixty-seven percent of the water arriving at the Mark Twain Lake is from streamflow and 22 percent from precipitation, whereas only 11 percent is from groundwater. There was a similar condition with the outflow water in the lake, with greater than 98 percent of water flowing out of the lake from evapotranspiration (210,000 m^3/day) and stream flow (731,000 m^3/day), in contrast to only 2 percent (18,000 m^3/day) through groundwater. Streamflow and evapotranspiration provides the largest outflow mechanism for the lake (Table 8). These data indicated that this is a surface-water-dominated lake, which is consistent with its setting in a claypan soil. Most of the contaminants are carried by surface runoff and flow through stream channels into the Mark Twain Lake. Thus, the riparian buffers upstream of the lake should emphasize the ability of stopping surface runoff.

Simulation results were compared to the results in Missouri from SWAT model performed by Ghidey et al. (2005) in the Goodwater Creek watershed. As previously mentioned, the SWAT model requires many parameters but also provides detailed output. Ghidey et al. (2005) indicated that the SWAT model (using default parameters) overestimated average annual streamflow by 32 percent, underestimated average annual sediment yield by 23 percent, and overestimated average annual atrazine loss by 8 percent. After calibration, the difference between measured and estimated average annual flow was less than 5 percent. Chidey et al. (2005) noted that the calibrated model did not estimate streamflow well on a daily basis and they wanted to improve streamflow estimation. Thus, SWAT performed overall simulation on both hydrology and pollutant transport in detail with mixed results. Comparatively, GFLOW focused on simulating the hydrology of the area and calibrated well. The parameters of hydrological component in SWAT might be improved by performing a pilot simulation of the area using GFLOW.

SUMMARY AND CONCLUSIONS

In this study, a steady-state, analytical-element, groundwater flow model was constructed in the upper part of the Mark Twain Lake watershed in northeastern Missouri, including the Crooked Creek monitoring site. The entire model domain represents approximately 6,000 square kilometers (~2,200 square miles) for the focus areas, Crooked Creek and Mark Twain Lake. The model was calibrated by 6 hydraulic head targets, 4 lake stage targets, and 5 baseflow flux targets by trial-and-error, UCODE, and PEST simulations. Calibration provided an updated estimate of significant parameters, including their degree of certainty. Parameters refined through the automatic technique yielded optional values about 5 m/day for regional hydraulic conductivity for model domain, the K about 100 m/day for alluvial deposits, and a recharge rate for this model about 0.0002 m/day (2.8 in/yr, about 7 percent of mean annual precipitation).

Established GFLOW model successfully demonstrated the surface-water-dominated hydrological pattern of the area. Through the use of particle tracking and flux inspection in the model, groundwater flow and potential source areas of nutrients to stream in the area were identified. Most of the flow is parallel to the creek and enters irregularly. NPS pollutants in groundwater are transported primarily downstream through highly permeable, alluvial channels. Groundwater inflow to the stream emanates only from a small zone immediately adjacent to the stream. Groundwater flow into these channels and reduce the time of traveling and increase the amount of NPS pollutants into Mark Twain Lake.

Combining the observations from the simulation above, it is noted that the buffers setting nowadays may not fit the conditions in northeastern Missouri. The future setting of the riparian management sites in this region might need adjustment to fit into this special condition. Moreover, the enhancement of reducing the effectiveness of surface runoff within the buffers would be positive, according to the watershed water balance in this study (Blanco-Canqui et al., 2004). Two possible adjustments of buffer setting would be helpful towards improving the ability of buffers in this specific claypan soil area. First, establish the buffers on the top of the alluvium deposits to cover the entire stream valley, which is approximately the width of the buffers (Figure 35). It may improve the denitritification efforts of the groundwater underneath the zones by increasing the contact time with roots within buffers. Second, with regard to the surface water, buffers should be installed on the edge of the alluvium and adjacent terraces to increase the interception of overland flow and NPS contaminants (Figure 36). This would reduce the amount of NPS pollutants right at the edge and prevent them entering into streams and infiltrating into groundwater within alluvium.

Finally, this research demonstrates the effectiveness and advantages of using an analytic element model to investigate large scale groundwater flow systems and identify groundwater boundaries. Once more detail information are available, the model can also be easily modified to provide possibilities for further buffer development and in-depth investigations.

SUGGESTIONS FOR FUTURE WORK

Further research with the analytic element model may include the addition of elements, the refinement of model parameters and extra calibration points. For instance, soil infiltration tests within the river valley and upland area could help distinguish the recharge rate that should be used in the model. The model calibration results could also be improved by adding extra monitoring wells in the modeling domain. The simulation may also be improved and the uncertainty in parameter values reduced by refining existing data and incorporating additional stream discharges and test points in upland areas into the model calibration. This may provide a more random distribution of weighted residuals and reduce the uncertainty within the model (Hunt et al, 2000).

Other parameters whose affects should be investigated more closely include stream resistances, base elevation of the streams, and the component of overland flow from gullies. Large sinkholes developed in the underlying limestone bedrock (for example, Mark Twain Cave) might have significant effects on local scale hydrology. Tracer tests could help contribute model results and locate possible flow inflow and outflow of sinkholes. Multilevel piezometers at riparian buffers could help discover more detail about the distribution of flow and contaminants in depth (Einarson and Cherry, 2002; Wineland, 2002).

The calibrated analytic element model can also be used as a "screening model" (the process of TMR or telescopic mesh refinement method) to develop boundary conditions for finite-difference models (MODFLOW) that may incorporate greater geologic details at the local scale (Hunt et al., 1998; Leak et al., 1998; Feinstein et al., 2003; Haefner and Boy, 2003;

Hunt and et al., 2005; Hunt, 2006). The option to produce a finite difference grid is available in this newest version of GFLOW.

Overall, the established model provides an avenue for continued research involving groundwater flow distribution, possible contaminant transport path/source and hydrological behavior, and the relationship of Mark Twain Lake in northeastern Missouri to the hydrological system.

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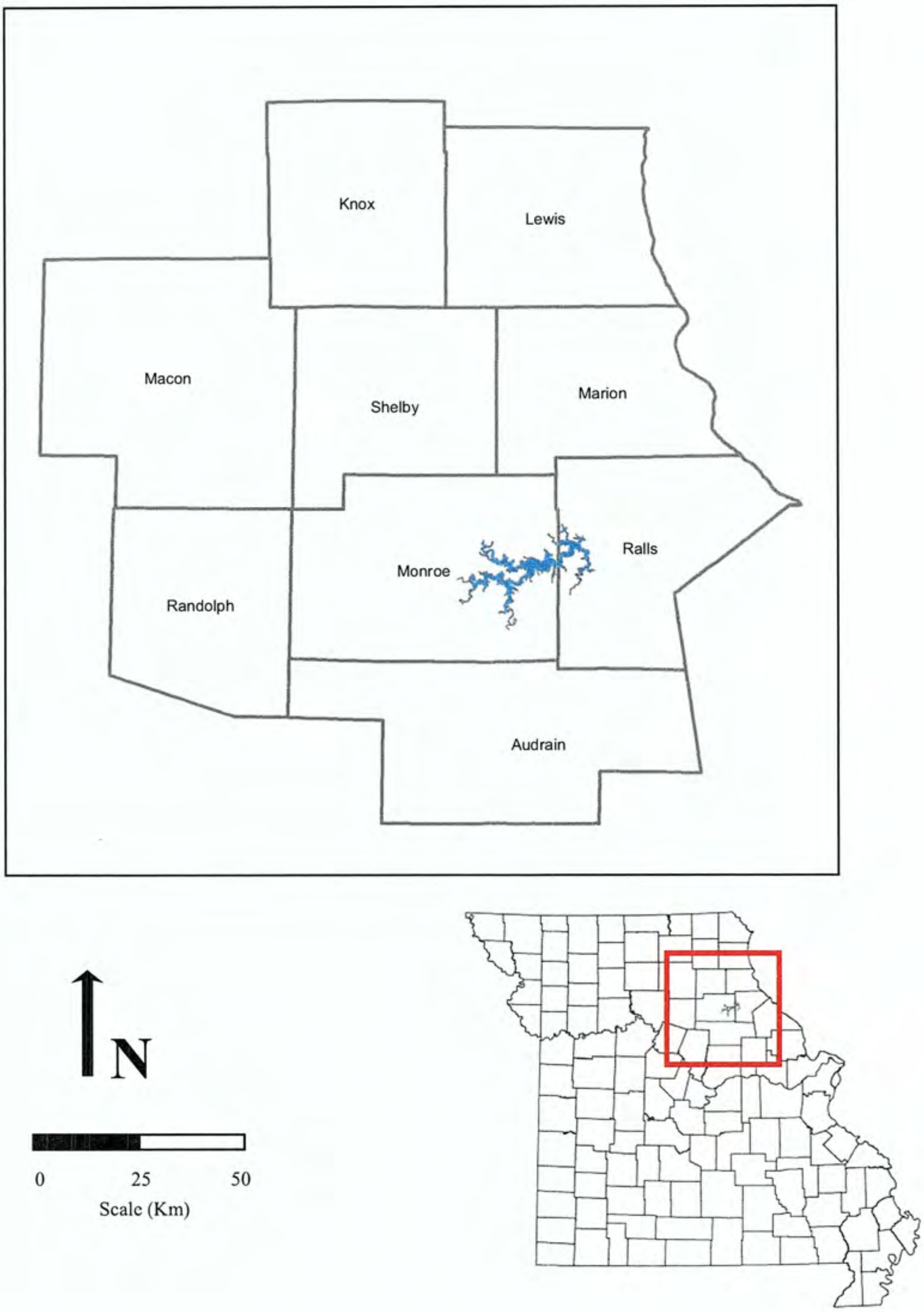


Figure 1. Location of Mark Twain Lake and adjacent counties.

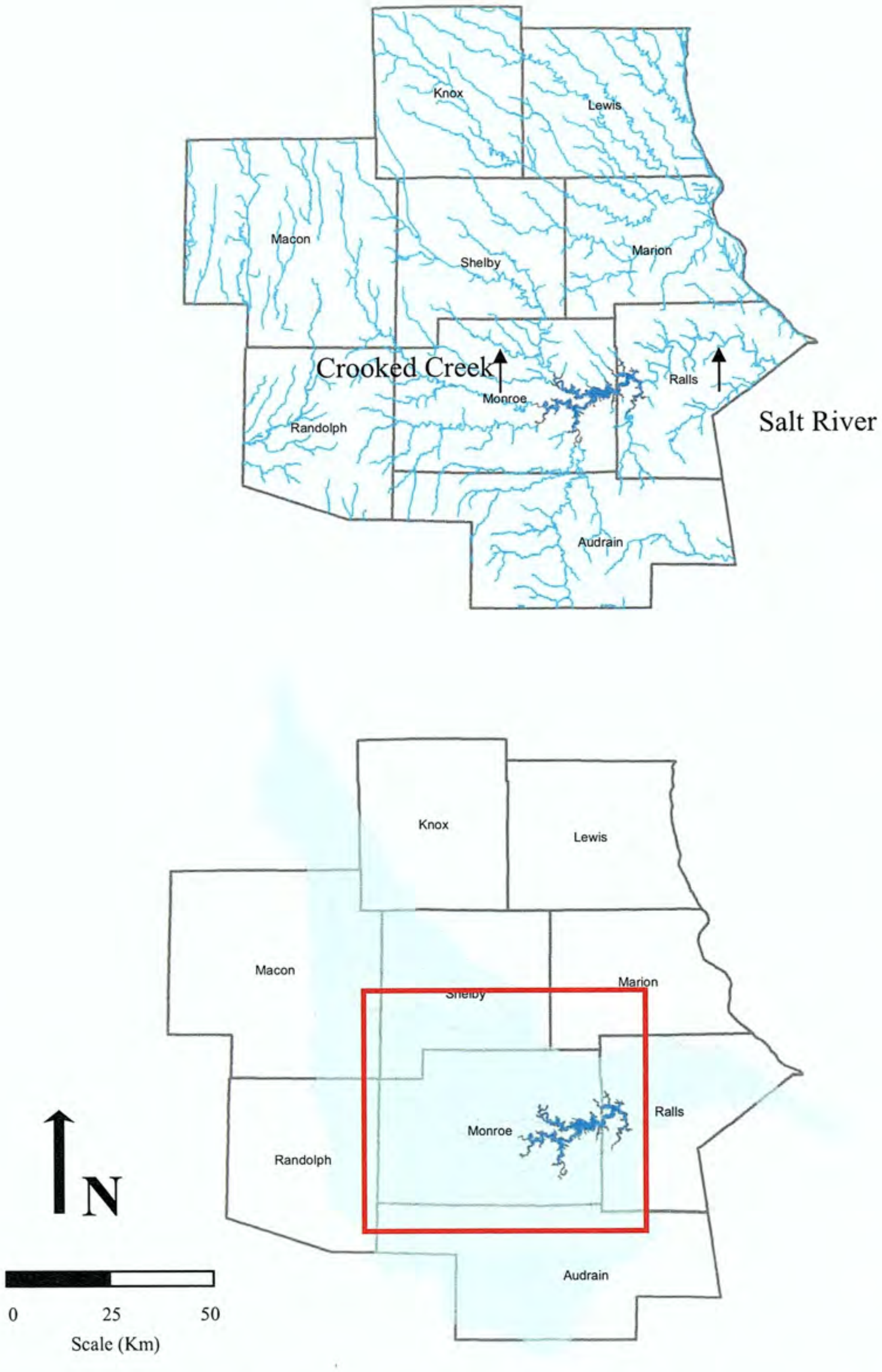


Figure 2. Watersheds of Mark Twain Lake and Salt River downstream. The red box is the area that was used for modeling in this study.

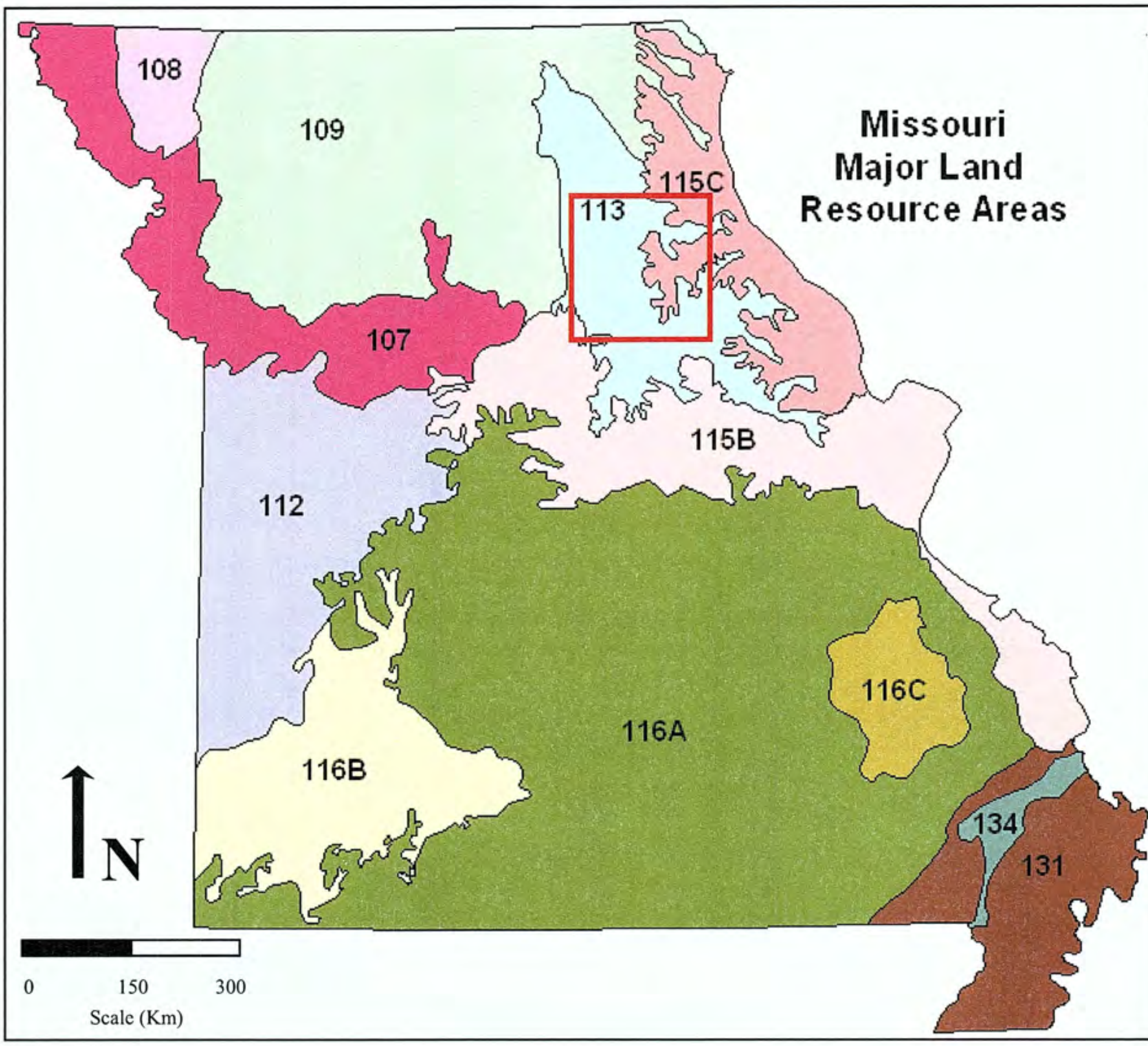


Figure 3. Missouri Major Land Resource Areas. MLRA 107: Iowa and Missouri Deep Loess Hills; MLRA 108: Illinois and Iowa Deep Loess and Drift; MLRA 109: Iowa and Missouri Heavy Till Plain; MLRA 112: Cherokee Prairies; MLRA 113: Central Claypan Areas; MLRA 115: Central Mississippi Valley Wooded Slopes; MLRA 116A: Ozark Highland; MLRA 116B: Springfield Plain; MLRA 116C: St. Francois Knobs and Basins; MLRA 131: Southern Mississippi Valley Alluvium; MLRA 134: Southern Mississippi Valley Silty Uplands; Red block is the study area.

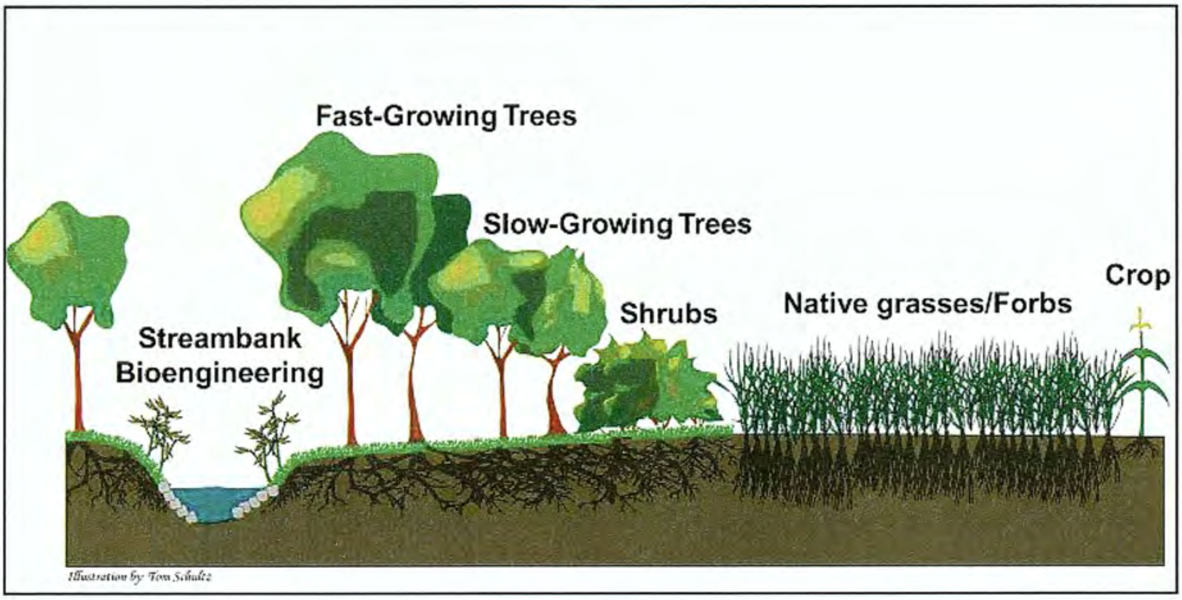


Figure 4. Multispecies riparian management system including the woody (trees and shrubs) and non-woody (grasses/forbs) zones between the stream and the crop field (http://www.buffer.forestry.iastate.edu/HTML/flexible.html).

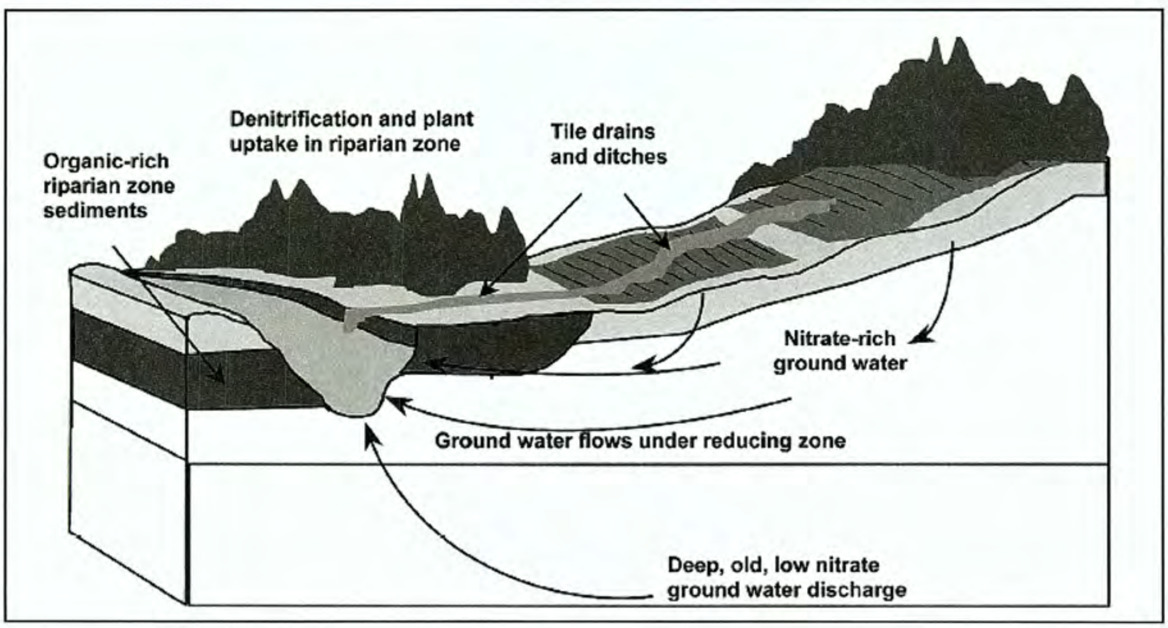


Figure 5. Conceptual model of flow where water avoids riparian zones through tiles or deeper groundwater flow (from Puckett, 2004).

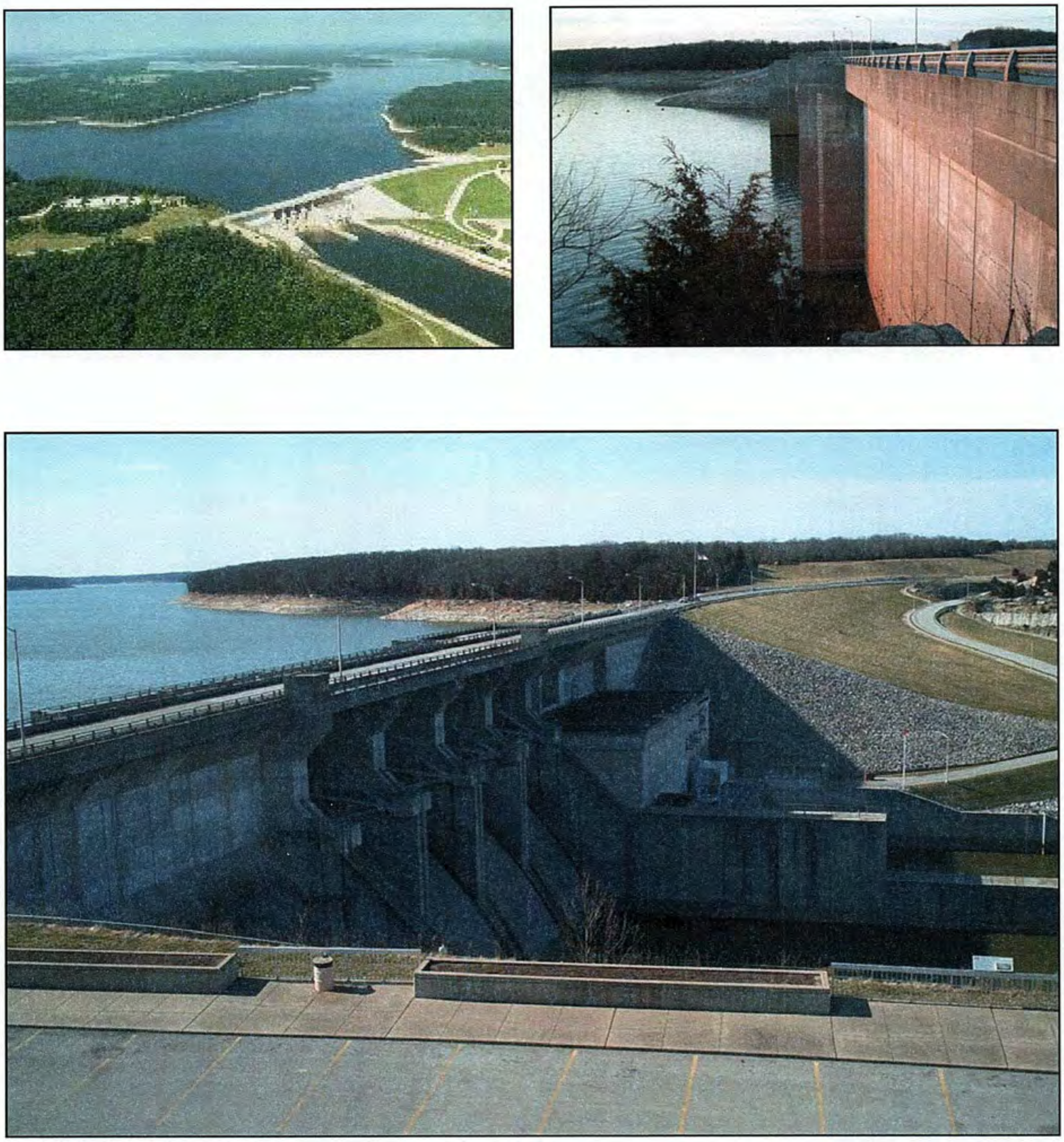


Figure 6. Photos of Mark Twain Lake and Clarence Cannon Dam (from USACE).

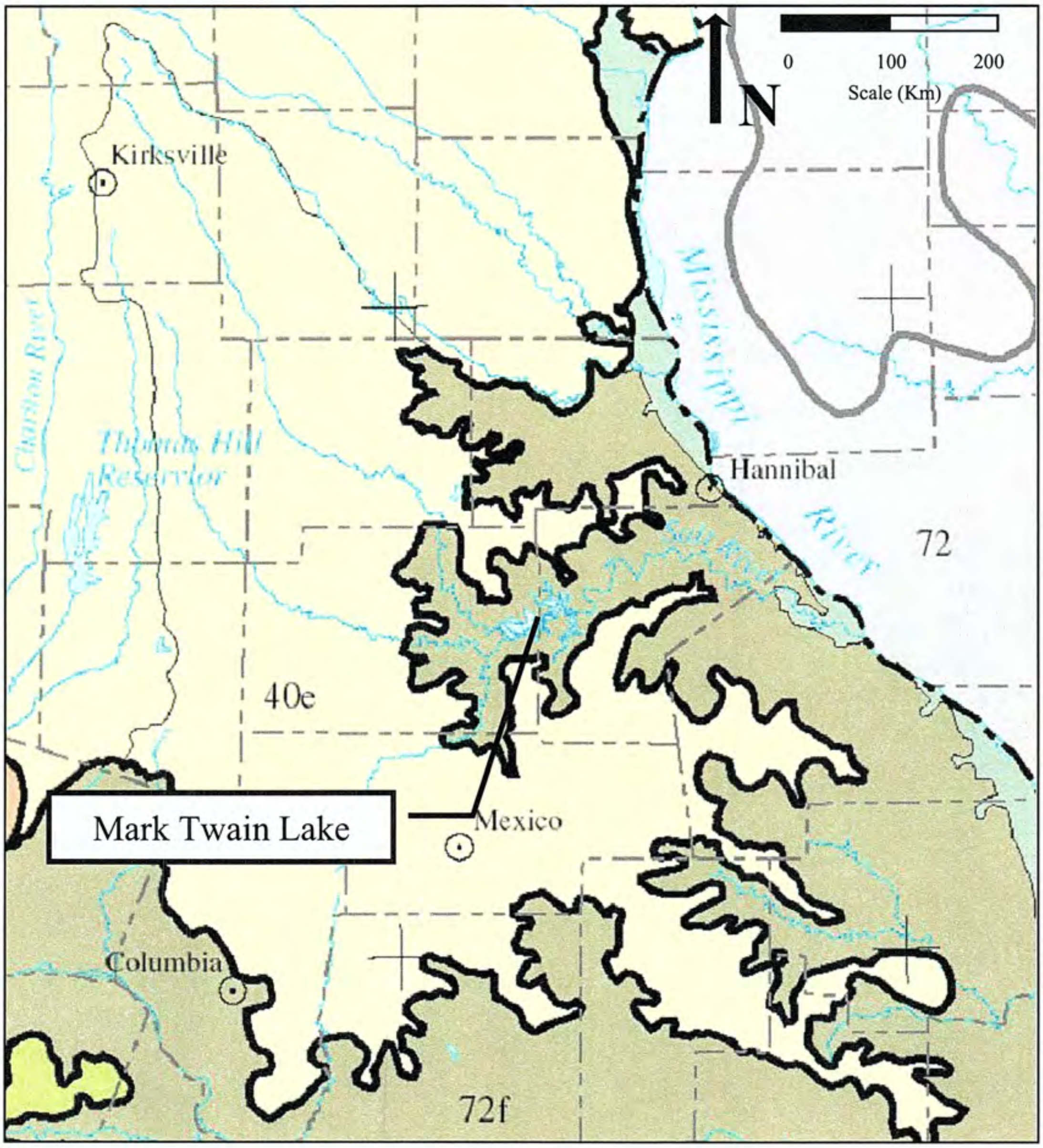


Figure 7. Ecoregions in the area surrounding Mark Twain Lake (from USEPA, 2000; 40e: Claypan Prairie; 72f: River Hills).

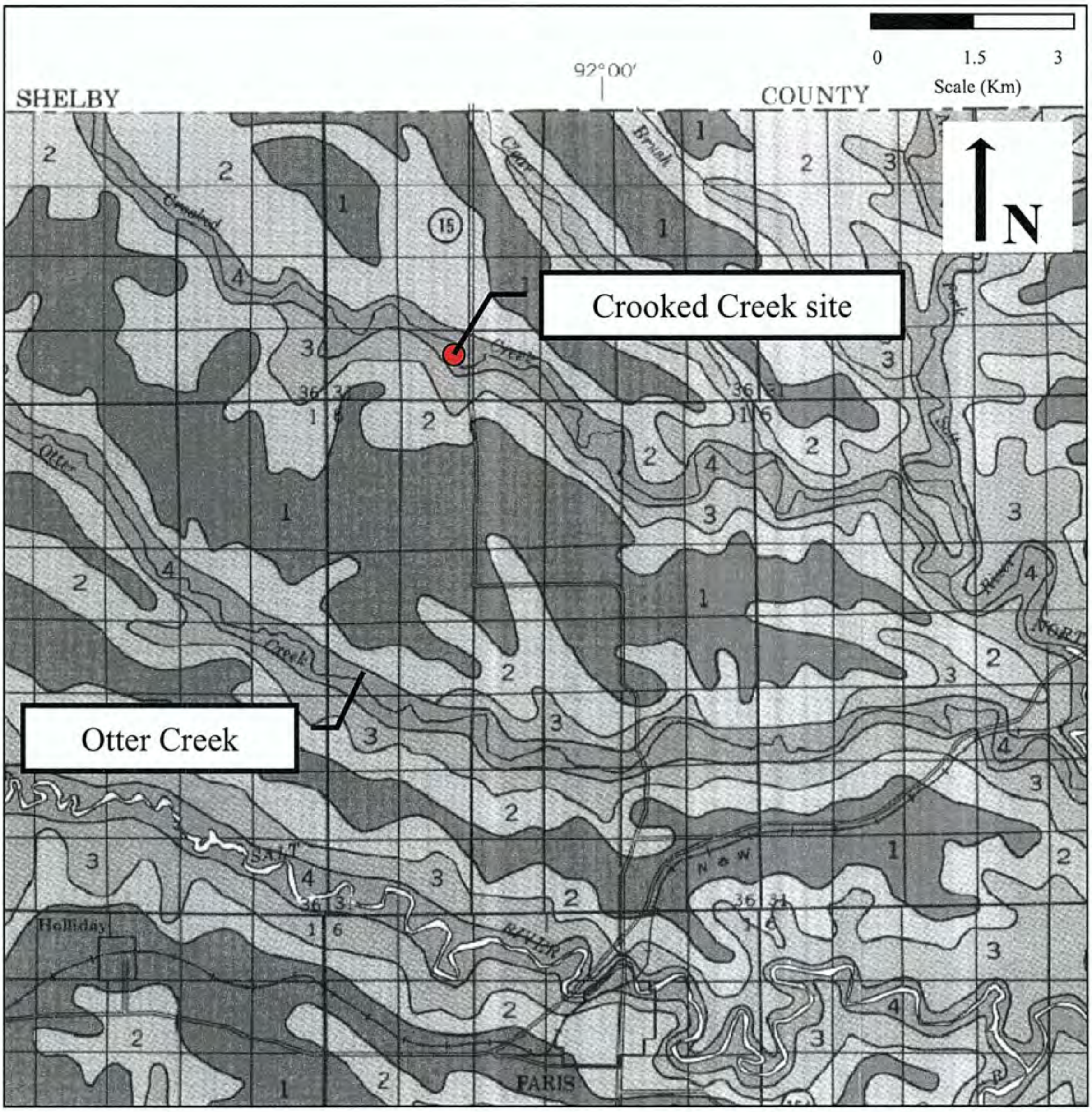


Figure 8. General soil map for Monroe County, Missouri. 1-Mexico-Putnam association: Deep, somewhat poorly drained and poorly drained, very slowly permeable, nearly level to gently sloping soils; on uplands. 2-Armstrong-Leonard association: Deep, moderately well drained and somewhat poorly drained, slowly permeable, moderately sloping to strongly sloping soils; on uplands. 3-Lindley-Keswick association: Deep, well drained and moderately well drained, moderately slowly permeable and slowly permeable, moderately sloping to steep soils; on uplands. 4-Piopolis-Blackoar-Arbela association: Deep, poorly drained and somewhat poorly drained, moderately permeable and slowly permeable, nearly level soils; on bottom lands and adjacent terraces (soil survey, USDA).

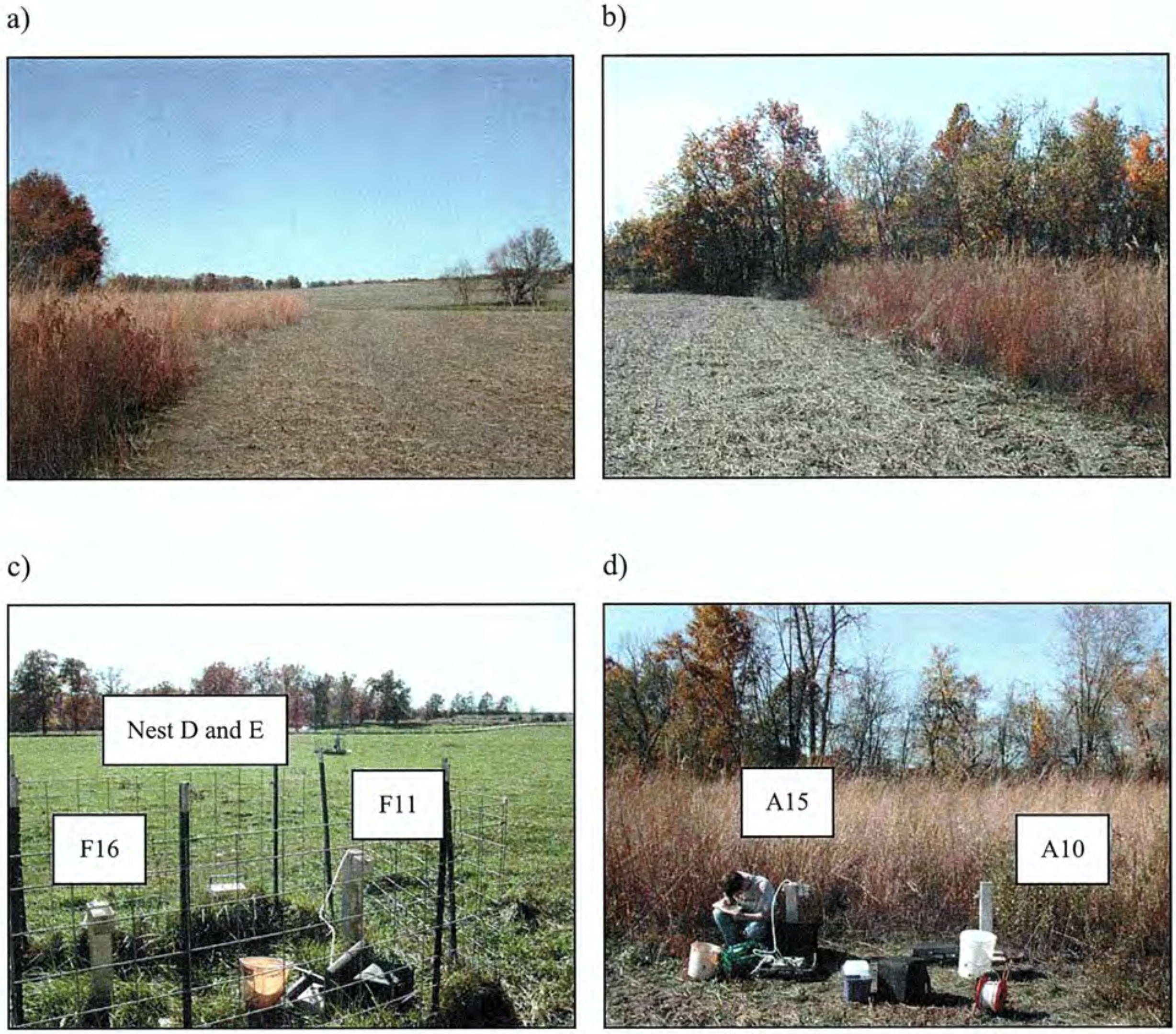


Figure 9. Settings of Crooked Creek site: (a) (b) grass zone between soybean field and forest; (c) pasture site with monitoring well nest F11 and F16; (d) monitoring well nest A10 and A15 installed between grass zone and field (B13 and B18 installed between grass zone and forest; C13 and C18 installed within forest zone).

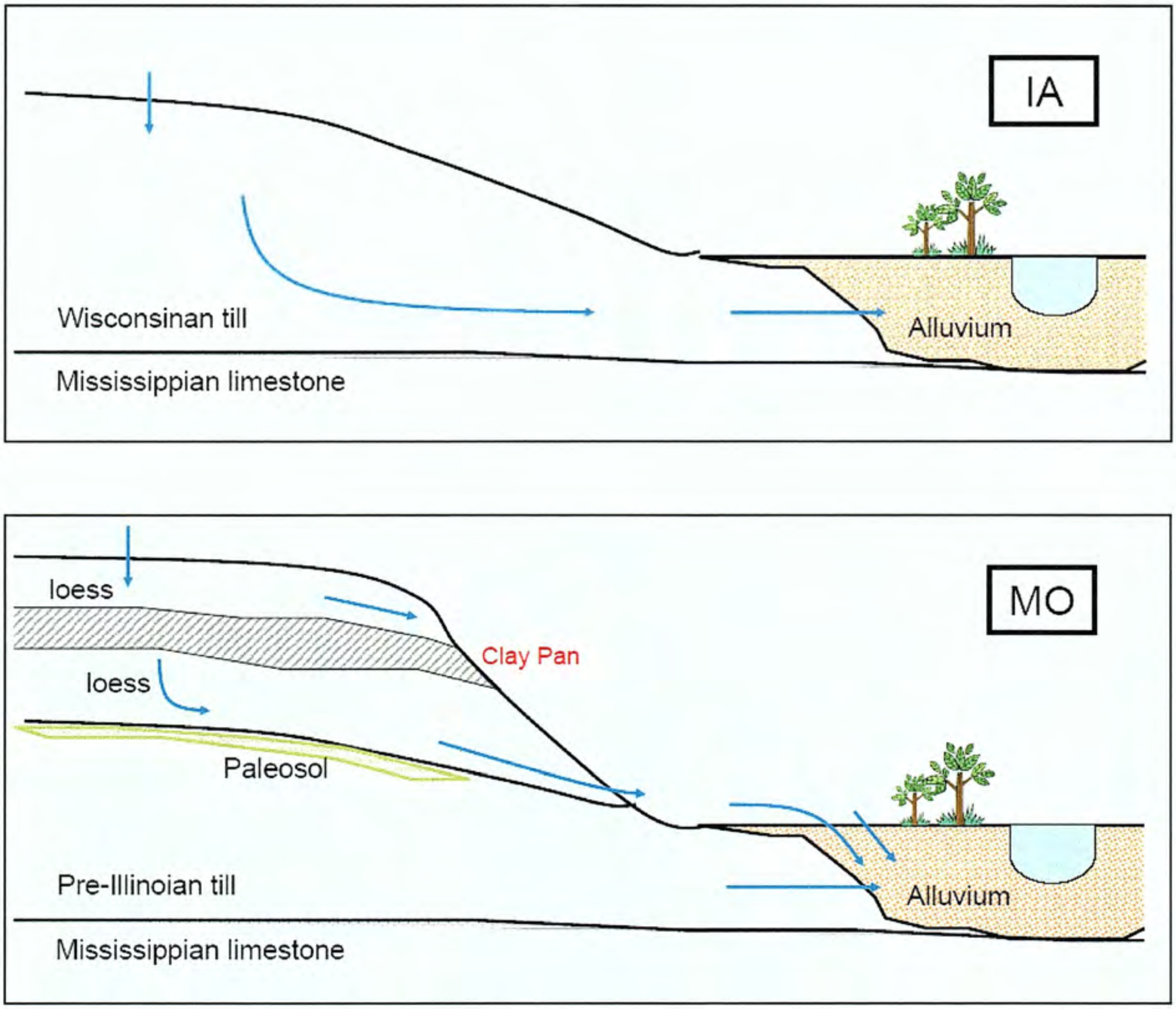


Figure 10. Conceptual models of shallow subsurface and groundwater flow for central Iowa and northeast Missouri.

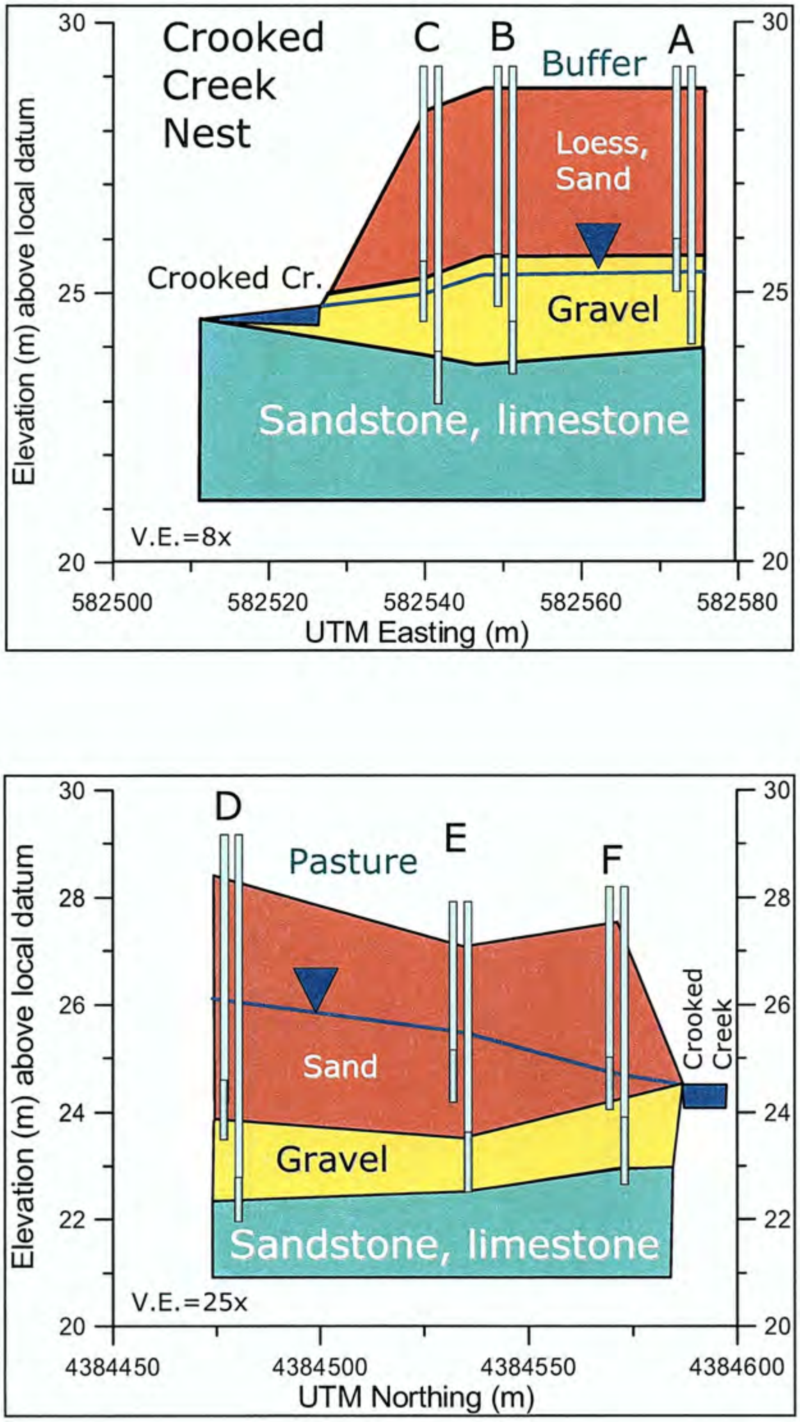


Figure 11. Cross sections showing stratigraphy and groundwater flow at the Crooked Creek sites. Water table shown by blue line and upside-down triangle (W.W. Simpkins, personal communication, 2005). Monitoring well nest A10 and A15 installed between grass zone and field; B13 and B18 installed between grass zone and forest; C13 and C18 installed within forest (as figure 9).

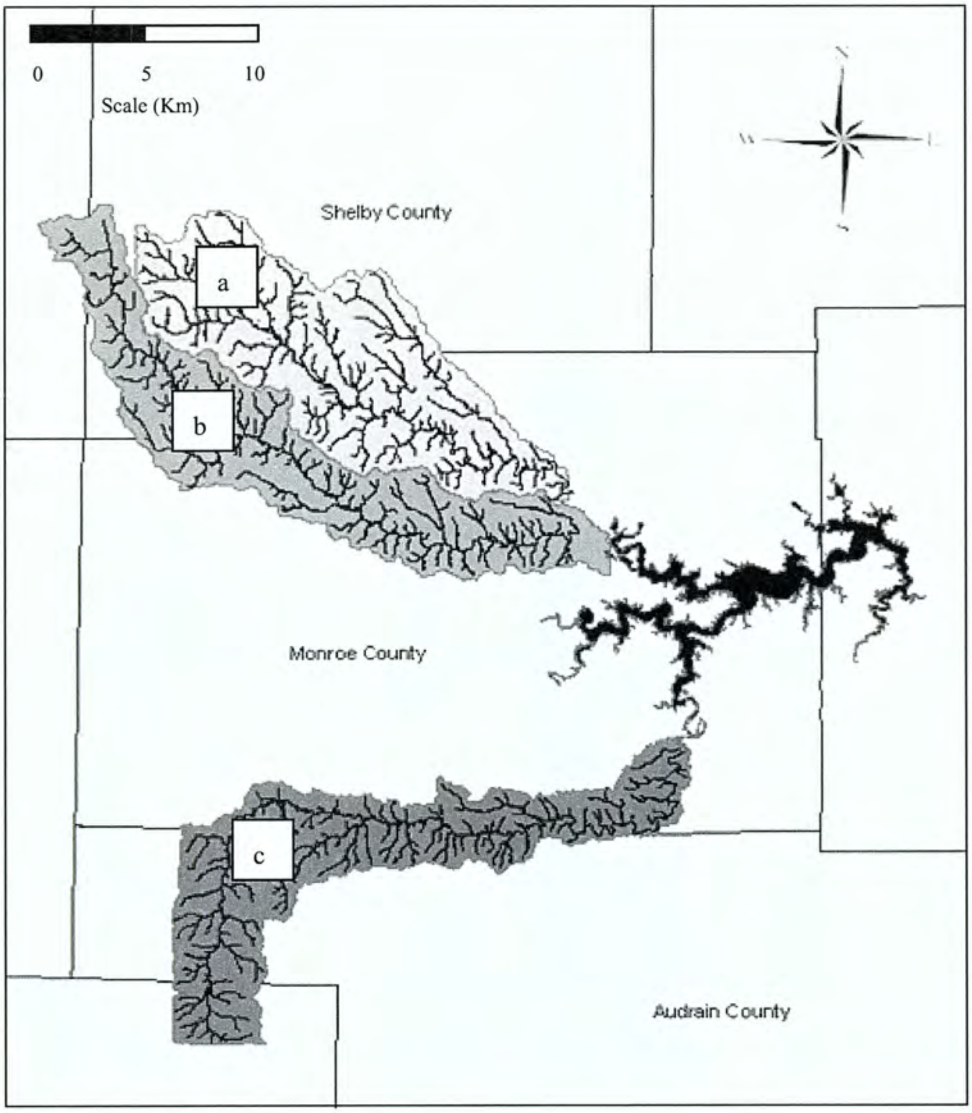


Figure 12. Study watersheds, including (a) Crooked Creek, (b) Otter Creek, and (c) Long Branch Creek.

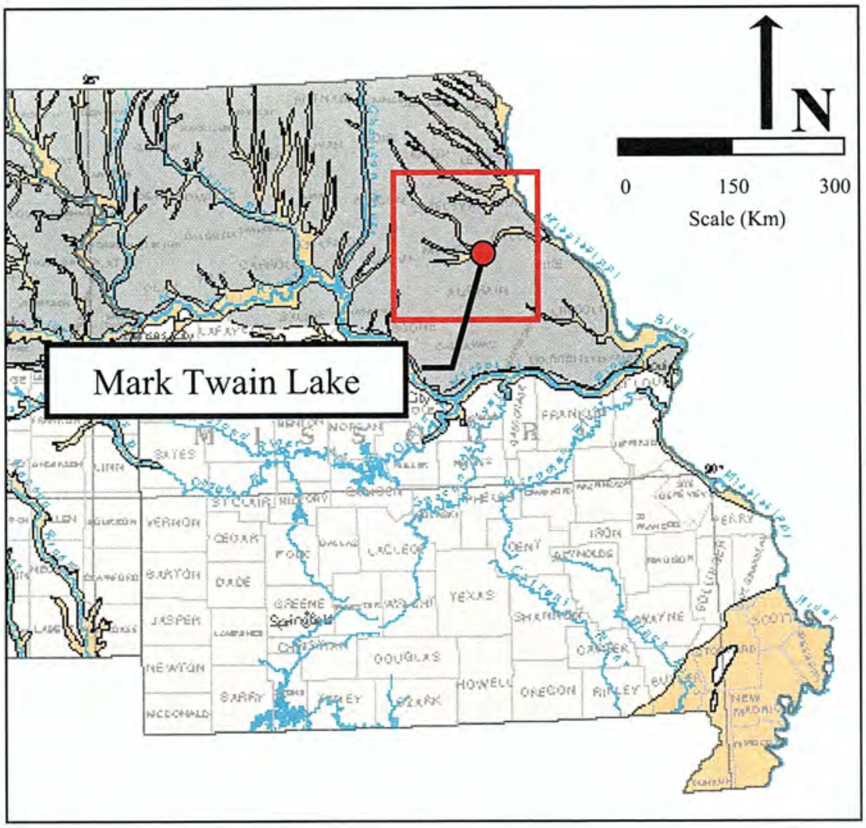


Figure 13. Map of surficial aquifer system: coarse-grained, unconsolidated deposits, mostly Quaternary age, compose surficial aquifer system in Missouri. Brown area presents coarse-grained glacial deposits, and stream-valley alluvium, while gray area presents till, loess, and fine-grained glacial-lake deposits (USGS, 1997). Red block is the focus area that was used for modeling in this study.

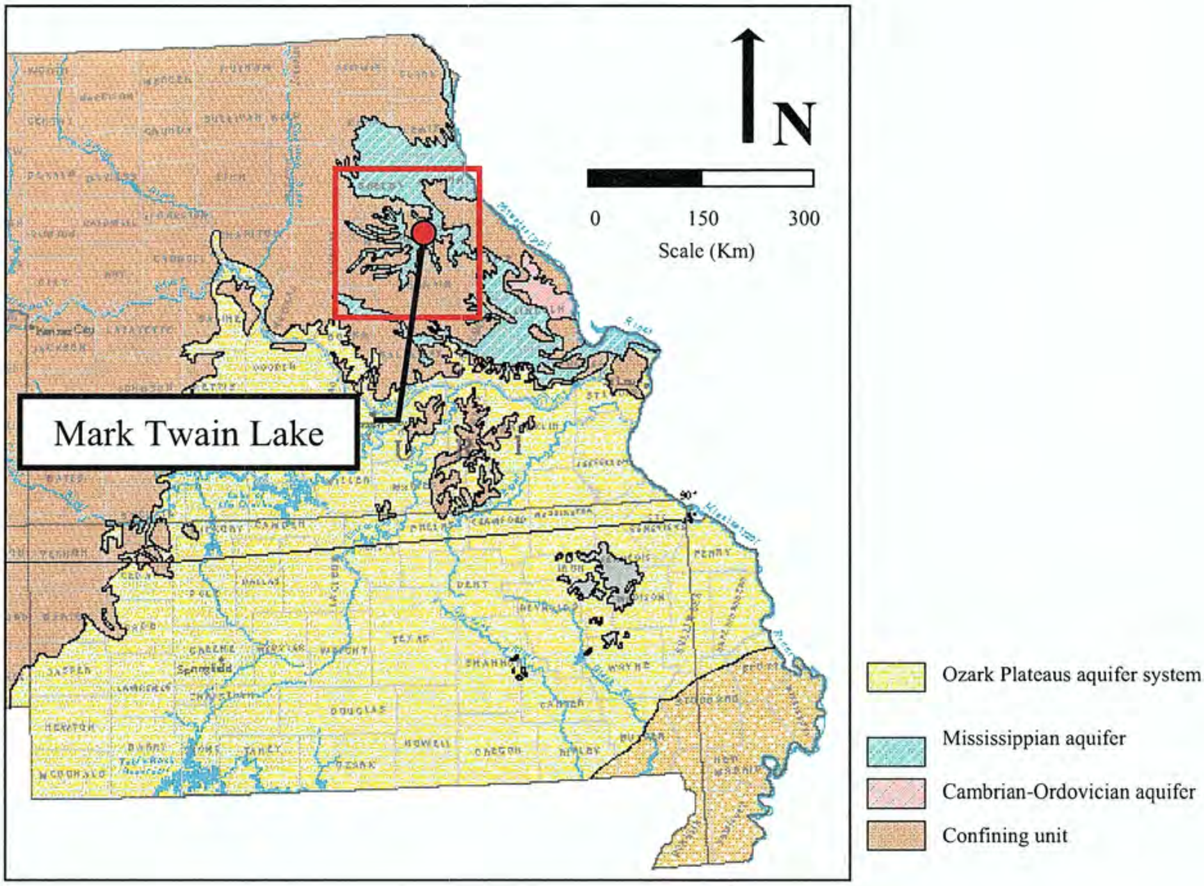


Figure 14. The extent of principal aquifer systems in Missouri. Brown area presents confining unit; blue area with oblique lines is Mississippian aquifer; yellow area is Ozark Plateaus aquifer system (consists of several units of Mississippian age to Cambrian age); red block is the study area (USGS, 1997).

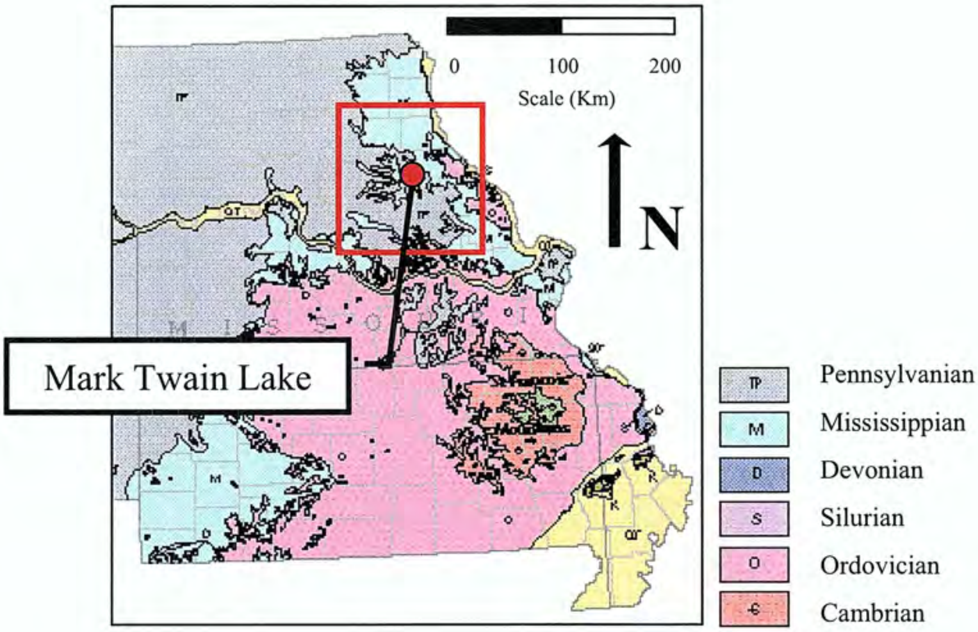


Figure 15. Generalized geologic map showing the extent of the major geologic units in Missouri. Purple area presents Pennsylvanian unit; blue is Mississippian unit; Red block is the study area (USGS, 1997).

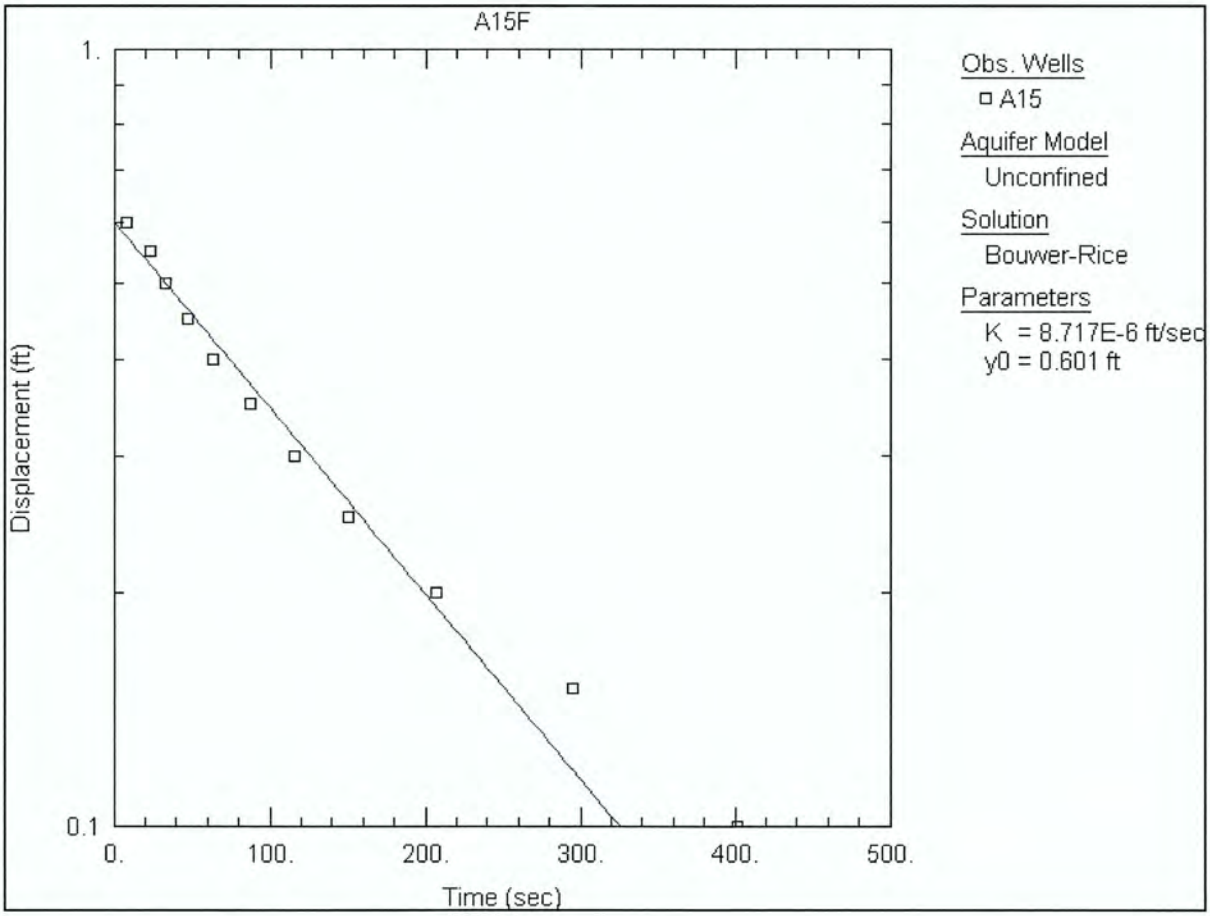


Figure 16. Slug test data and estimated K value for Well A15.

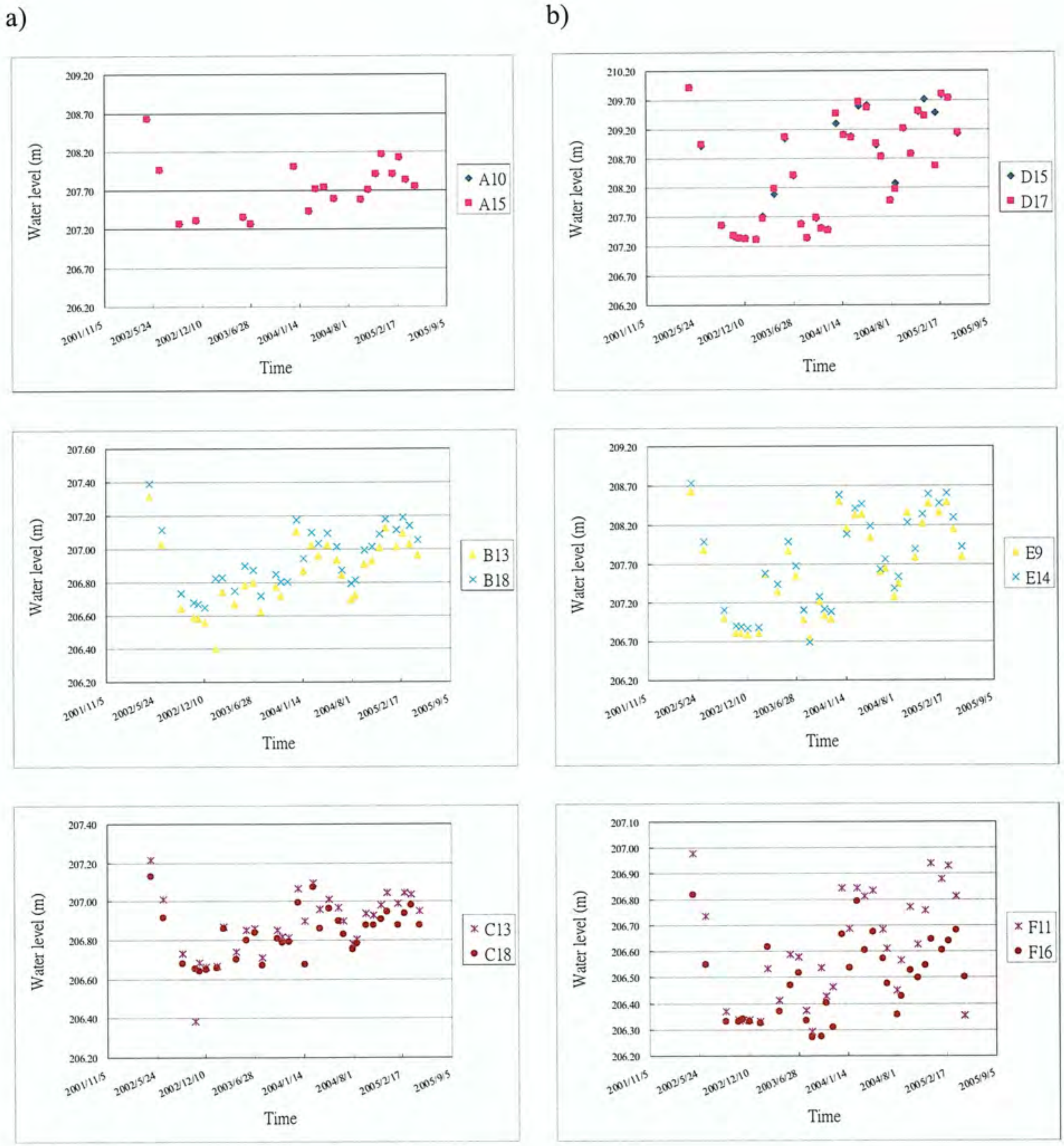


Figure 17. Water level (hydraulic head, meters above mean sea level) in the (a) buffer site (b) pasture site, at the Crooked Creek site. Water table of each well nest usually can be found between two wells at different depth. The upper head value probably is the best representation of the water table.

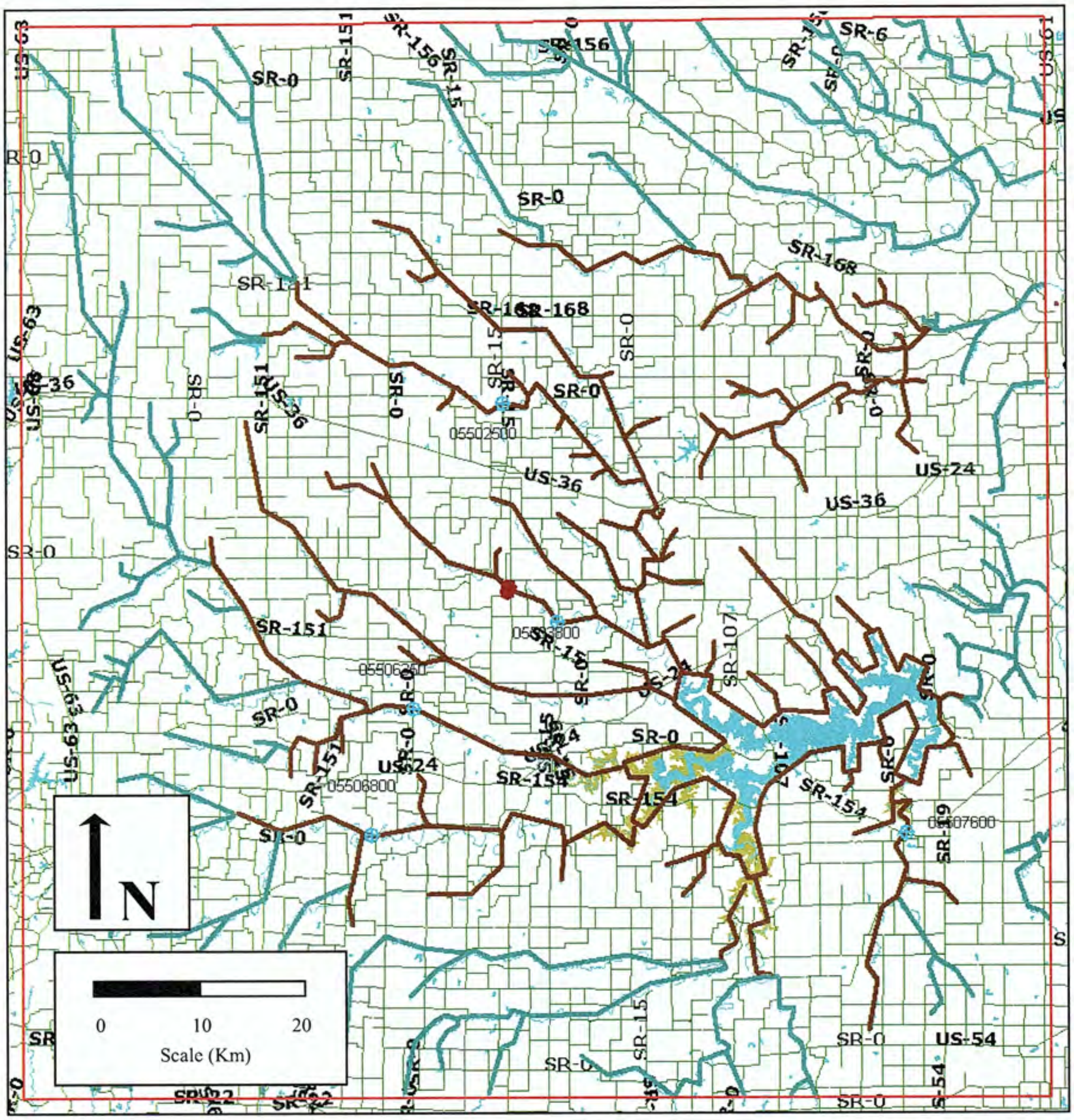


Figure 18. GFLOW model domain constructed using BBM base maps (includes roads and hydrology).

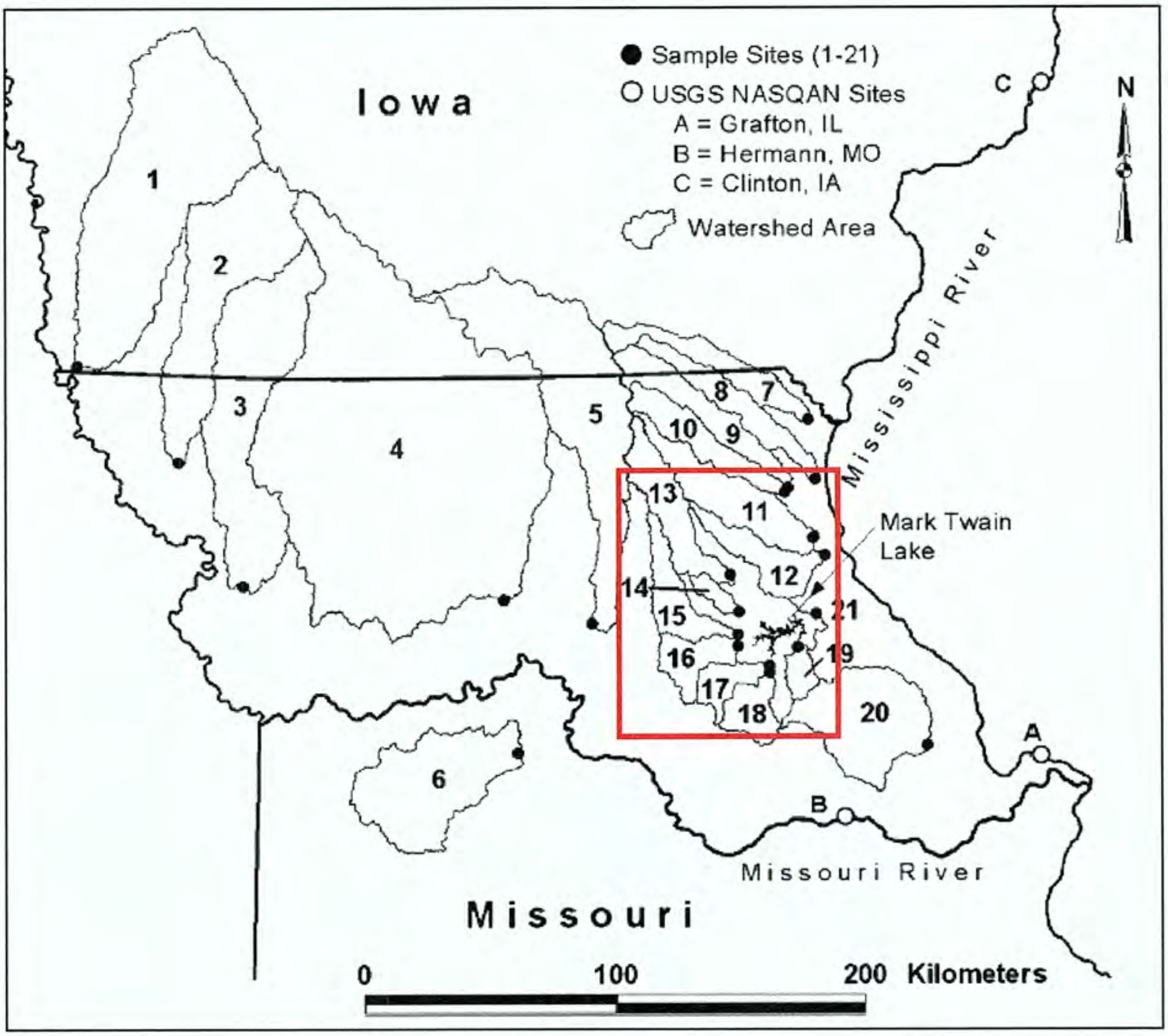


Figure 19. Watersheds within the GFLOW model domain (from Lerch et al., 2003) including 13-North Fork, 14-Crooked Creek, 15-Middle Fork, 16-Elk Fork, 17-Long Branch Creek, 18-South Fork Salt River and 19-Lick Creek. Red box is the study area.

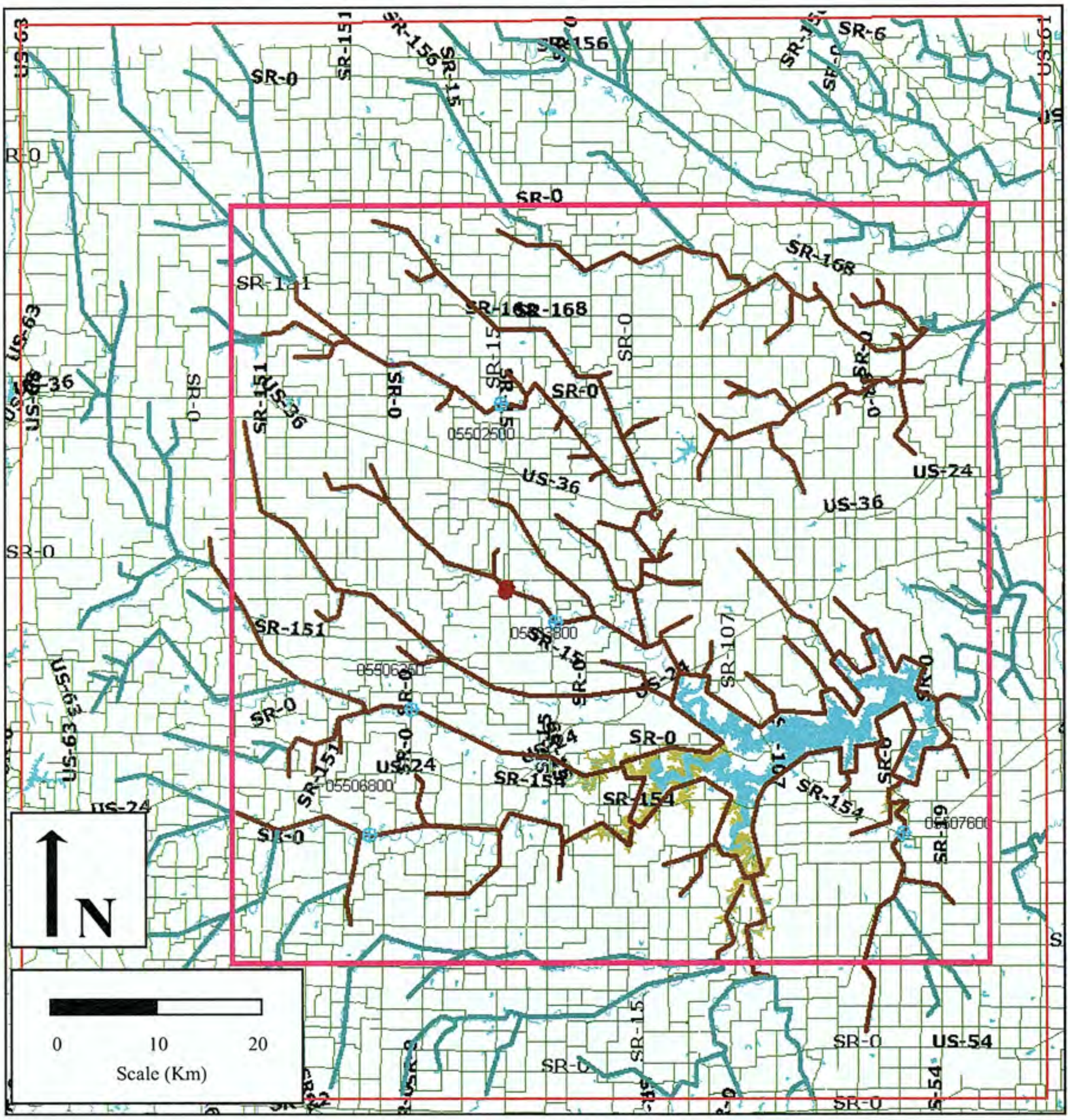


Figure 20. Model domain showing far-field and near-field areas. Brown lines represent near-field elements, while blue-greenish lines indicate far-field elements. Red box indicates the area to which recharge was applied over the entire model domain. Purple box indicates the near-field area.

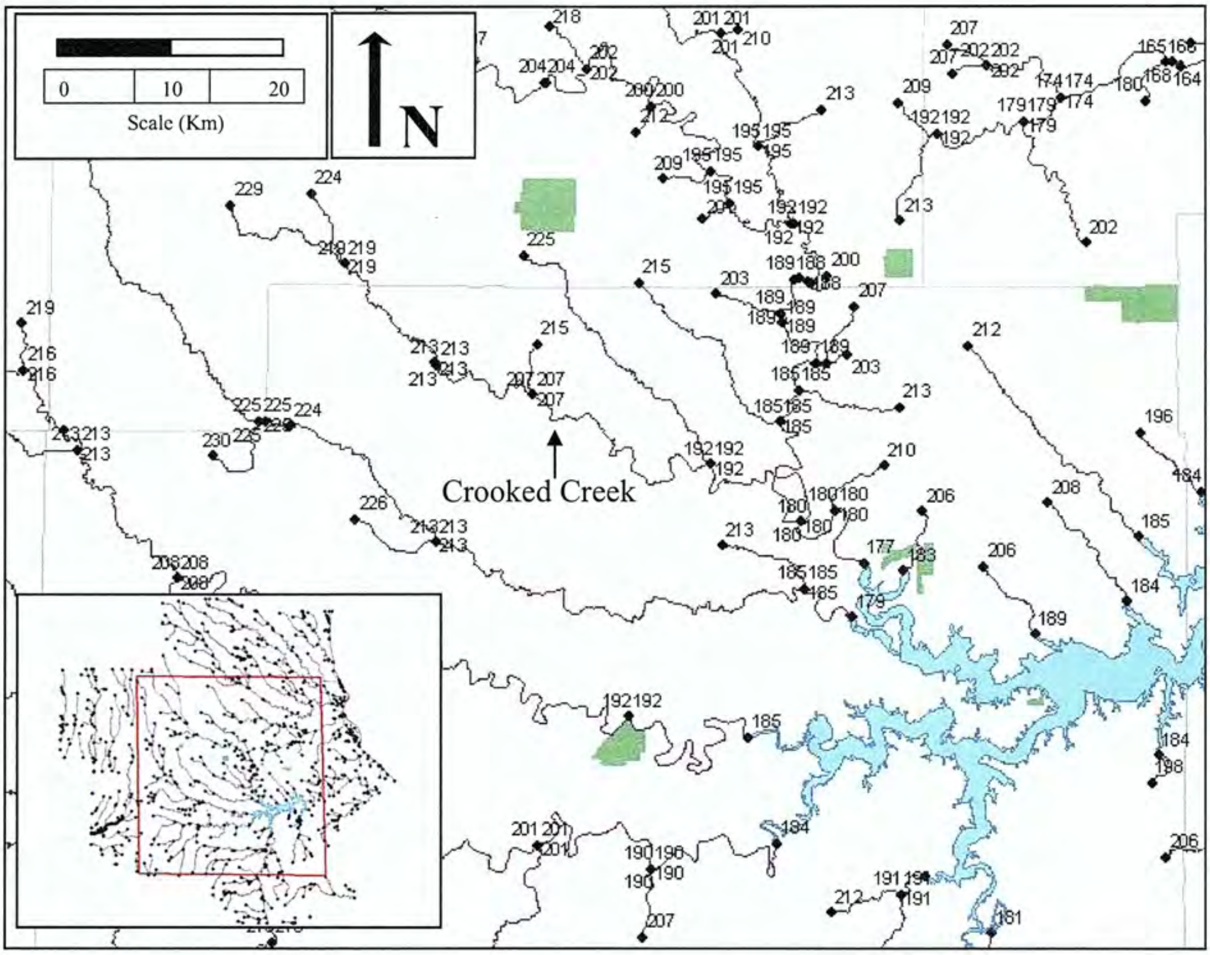


Figure 21. Elevations (meters) of stream segment intersections calculated using ArcView "givemepoints" (Appendix A; http://arcscripts.esri.com/details.asp?dbid=13300)

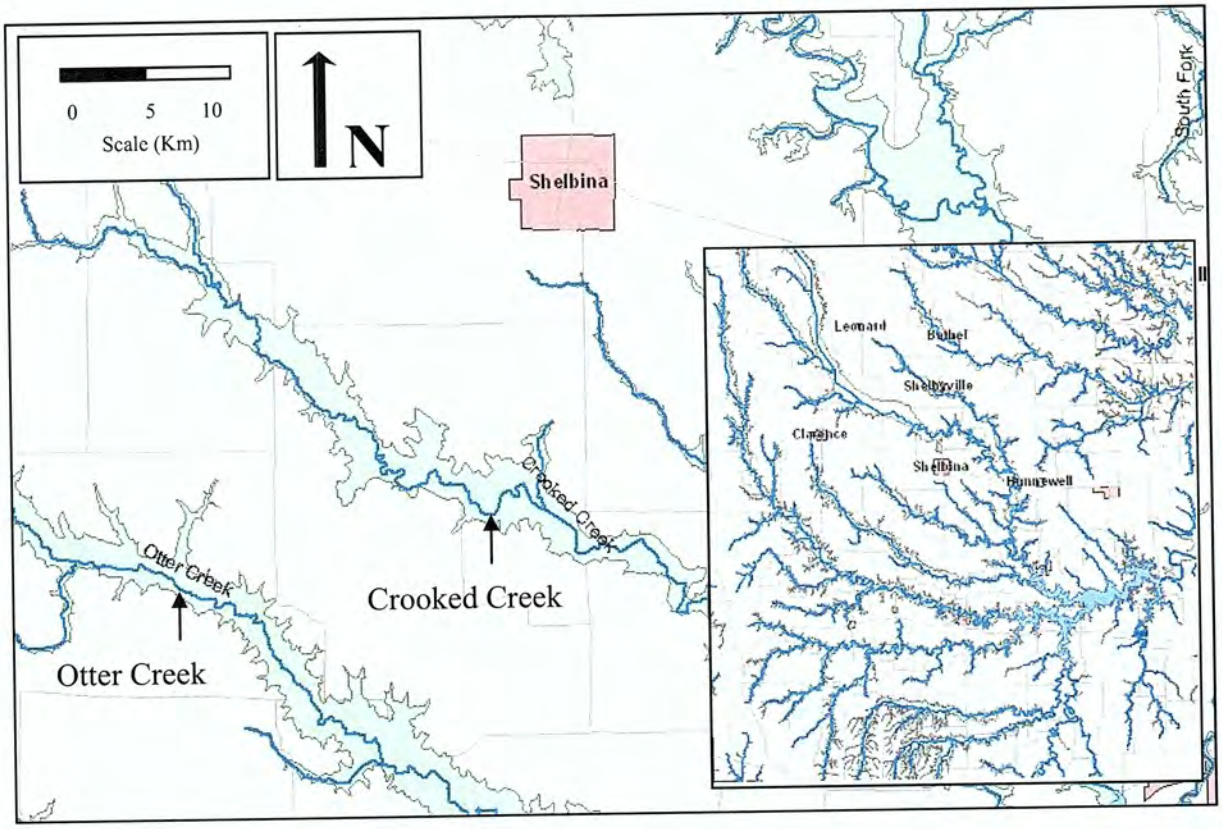


Figure 22. Mapped alluvial deposits along streams in the Mark Twain Lake watershed that were used to identify inhomogeneities in the model (Missouri Spatial Data Information Service, MSDIS, http://msdisweb.missouri.edu/index.htm).

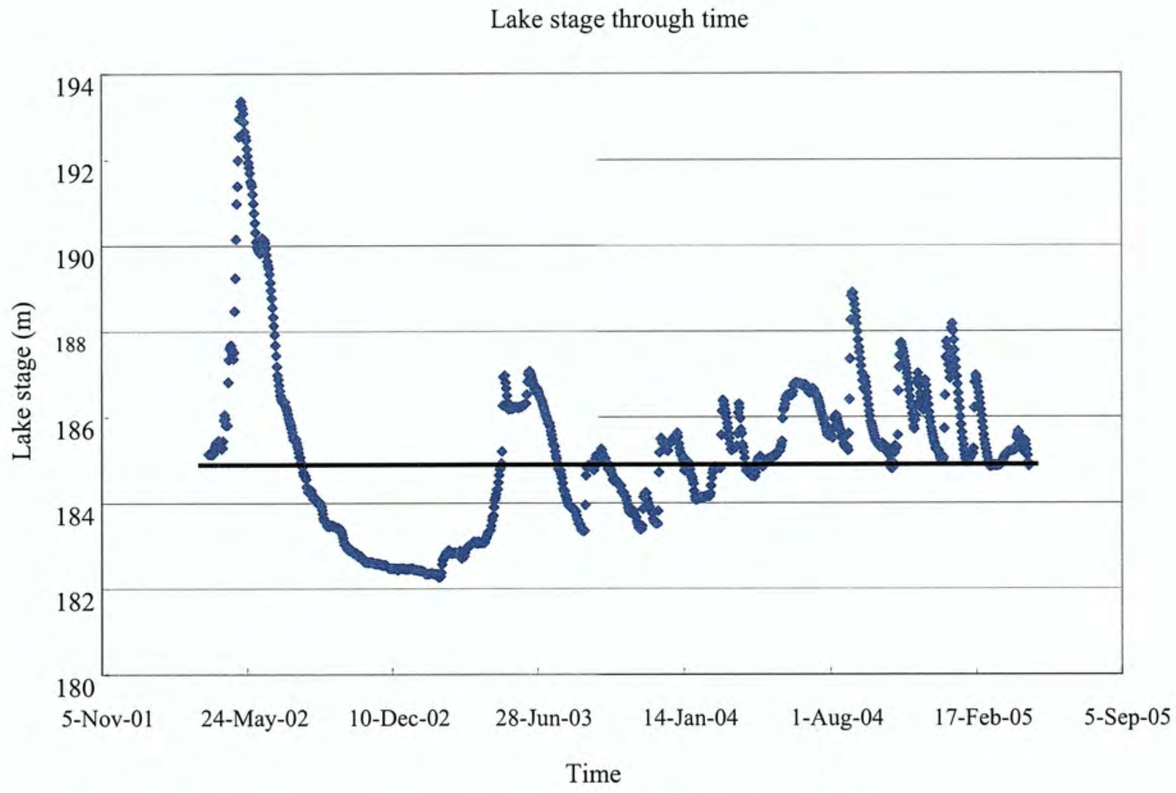


Figure 23. Stage of Mark Twain Lake from April 2002 through April 2005. Mean value of lake stage is 184.92 meters.

Figure 24. Locations of USGS gauging stations in the model domain (from USGS, 2005).

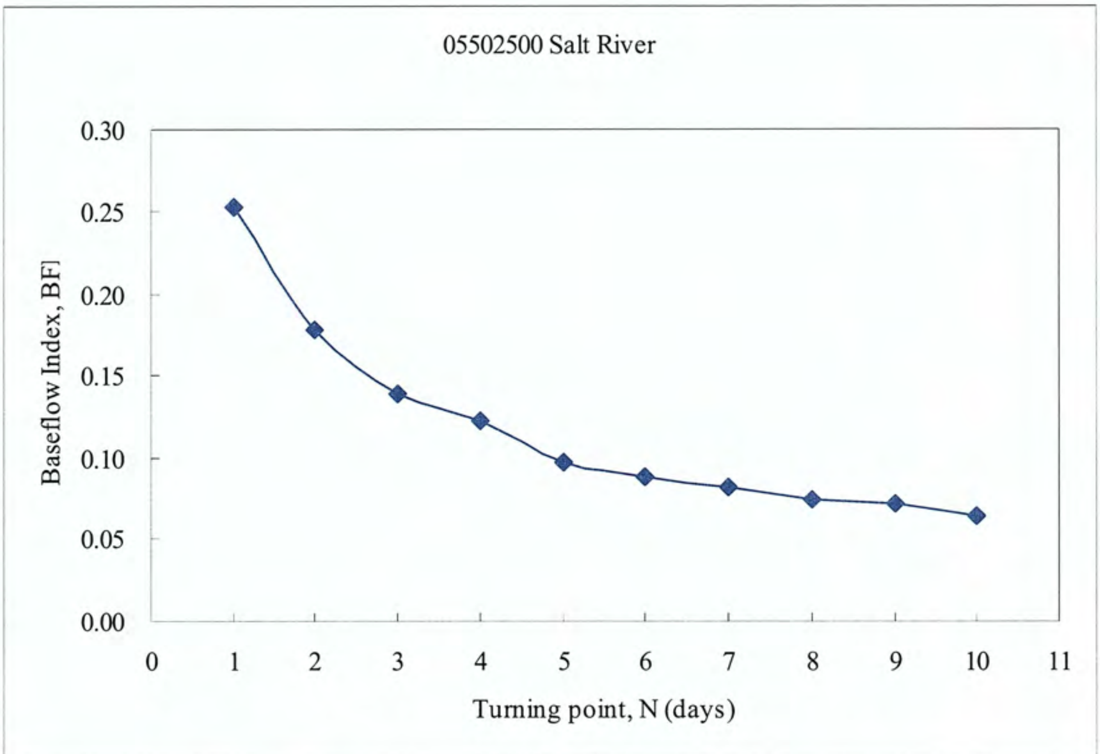


Figure 25. Relationship between baseflow index and turning point (days) for USGS Salt River gauging station (05502500). In this example, the turning point N equals 3, where results in a BFI=0.139.

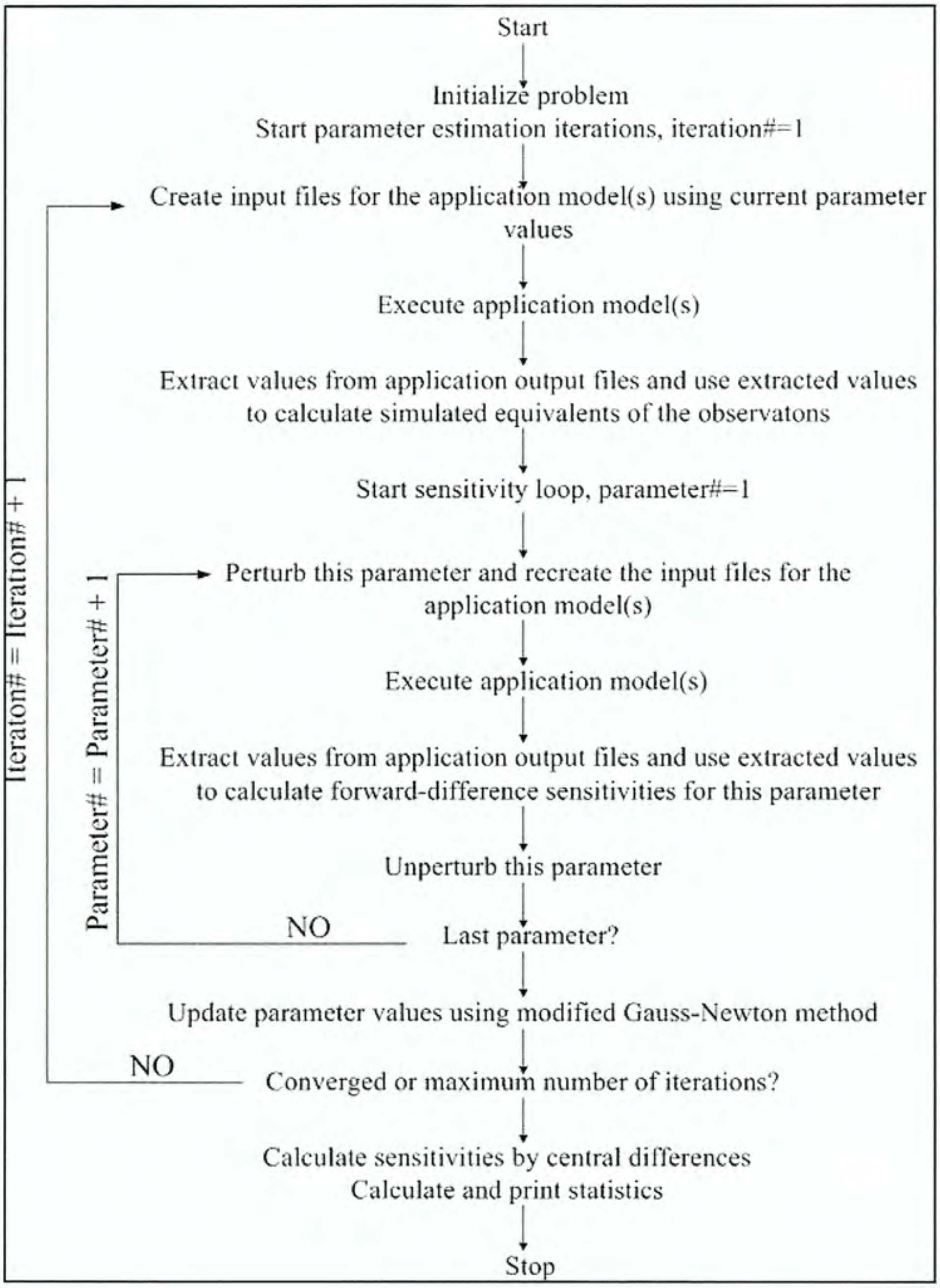
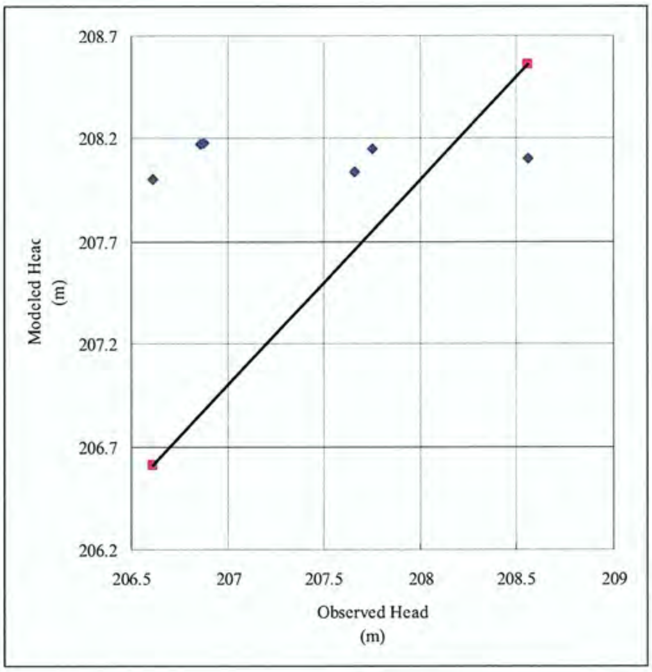
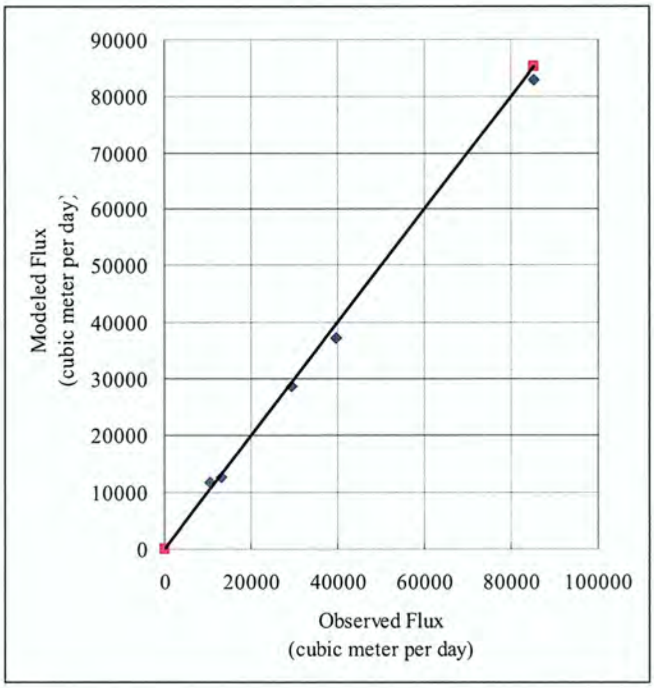


Figure 26. Flowchart for estimating parameters with UCODE (Poeter and Hill, 1998)

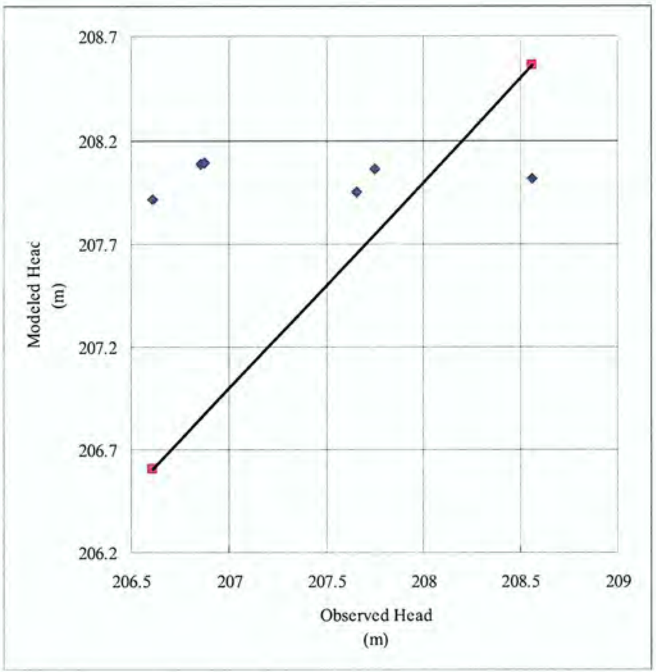


Number of Observations:	6
Maximum Difference:	1.4
Minimum Difference:	-0.5
Average Difference (AD):	0.7
Median Difference (MAD):	0.8
Mean Absolute Difference:	0.9
RMS Difference:	1
Sum of Squared Differences:	5.9

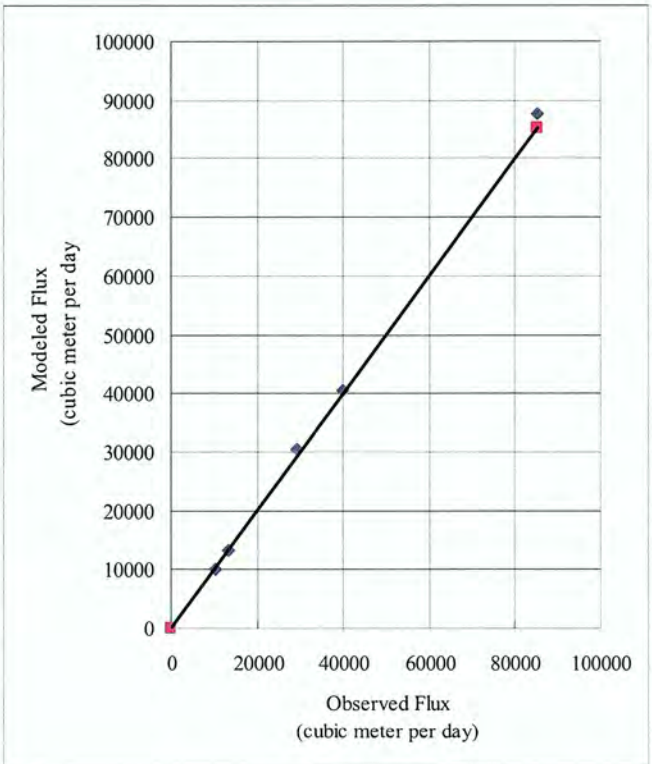


Number of Observations:	5
Maximum Difference:	1328.3
Minimum Difference:	-2475.7
Average Difference (AD):	-962.5
Median Difference (MAD):	-719.5
Mean Absolute Difference:	1493.8
RMS Difference:	1670.9
Sum of Squared Differences:	13959793.7

Figure 27. Calibration statistics and calibration curve for head and flux values by manual (trial-and-error) calibration.

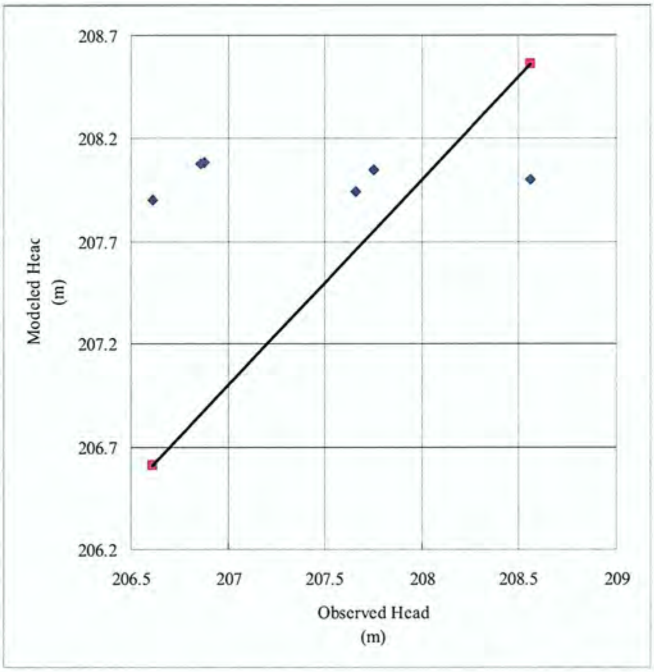


Number of Observations:	6
Maximum Difference:	1.3
Minimum Difference:	-0.5
Average Difference (AD):	0.6
Median Difference (MAD):	0.8
Mean Absolute Difference:	0.8
RMS Difference:	0.9
Sum of Squared Differences:	5.2

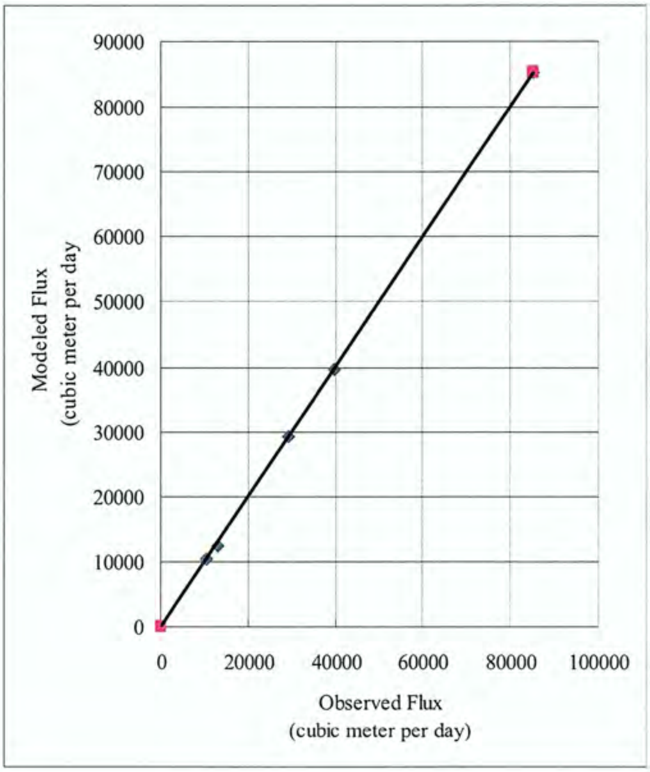


Number of Observations:	5
Maximum Difference:	2513.2
Minimum Difference:	-495.4
Average Difference (AD):	773.1
Median Difference (MAD):	783.5
Mean Absolute Difference:	992.3
RMS Difference:	1298.1
Sum of Squared Differences:	8425899.2

Figure 28. Calibration statistics and calibration curve for head and flux values by UCODE calibration.



Number of Observations:	6
Maximum Difference:	1.3
Minimum Difference:	-0.6
Average Difference (AD):	0.6
Median Difference (MAD):	0.8
Mean Absolute Difference:	0.8
RMS Difference:	0.9
Sum of Squared Differences:	5.1



Number of Observations:	5
Maximum Difference:	44.4
Minimum Difference:	-860.9
Average Difference (AD):	-218.9
Median Difference (MAD):	-65.4
Mean Absolute Difference:	242.2
RMS Difference:	399.7
Sum of Squared Differences:	798870.5

Figure 29. Calibration statistics and calibration curve for head and flux values by PEST calibration.

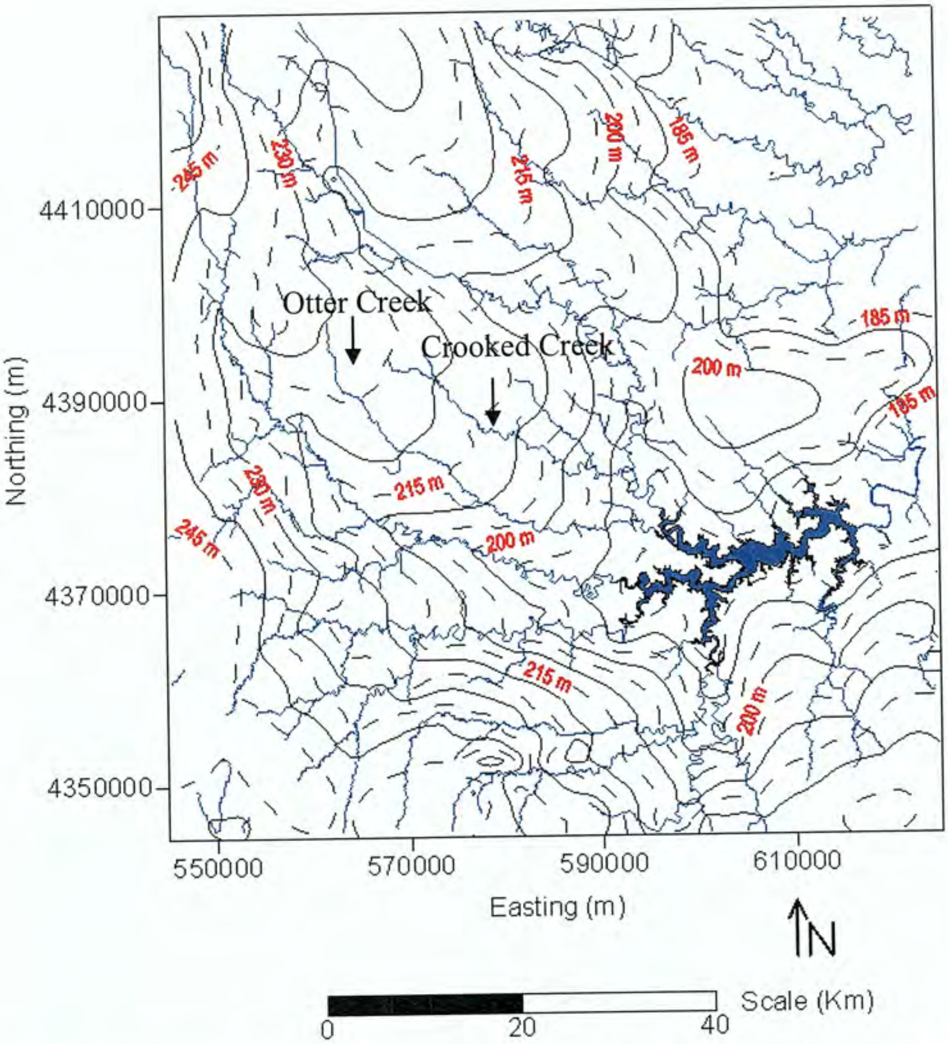


Figure 30. Contours (m) of the water table in the vicinity of Mark Twain Lake simulated by the AE model. Main contour interval is 10 m (solid lines) with intermediate contour at 5 m (dashed lines).

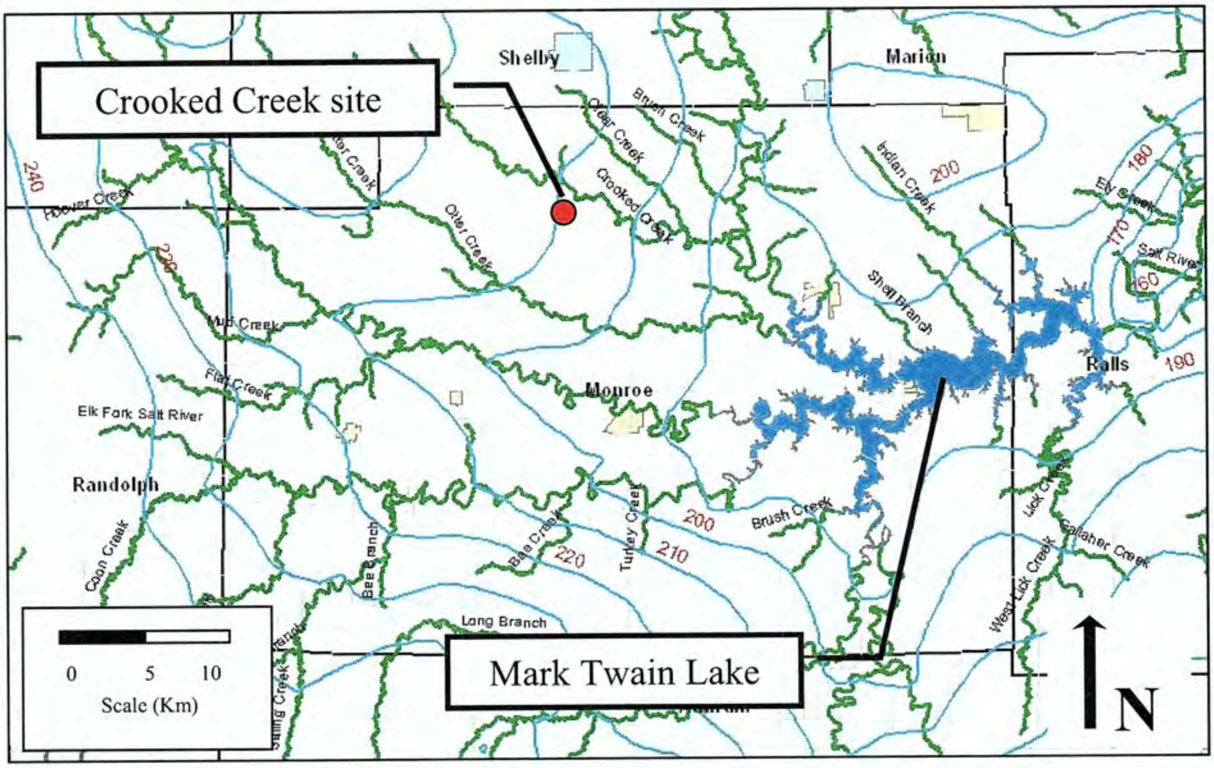
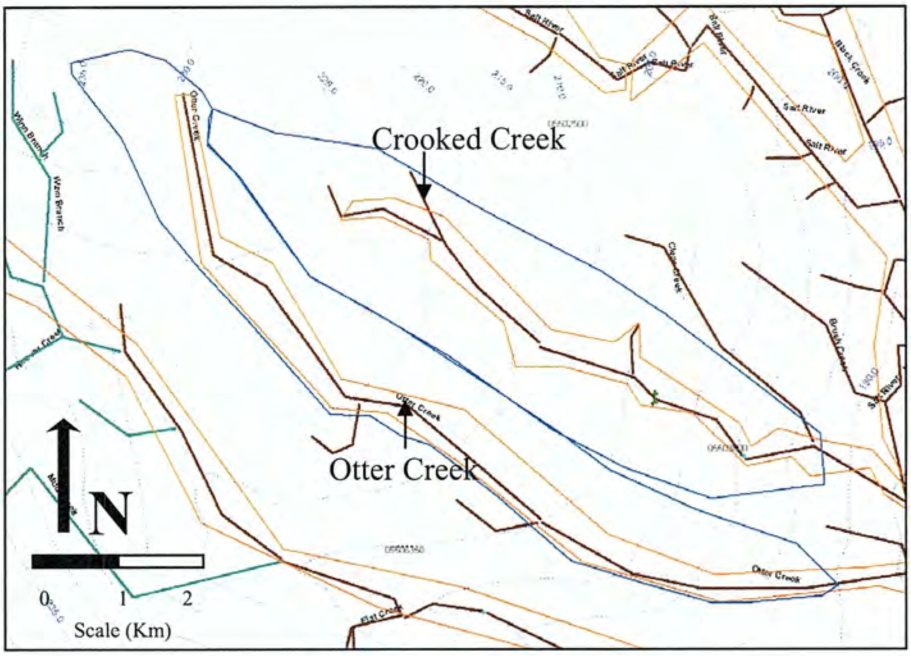


Figure 31. Water table configuration (meters) near Crooked Creek site and Mark Twain Lake.

a)



b)

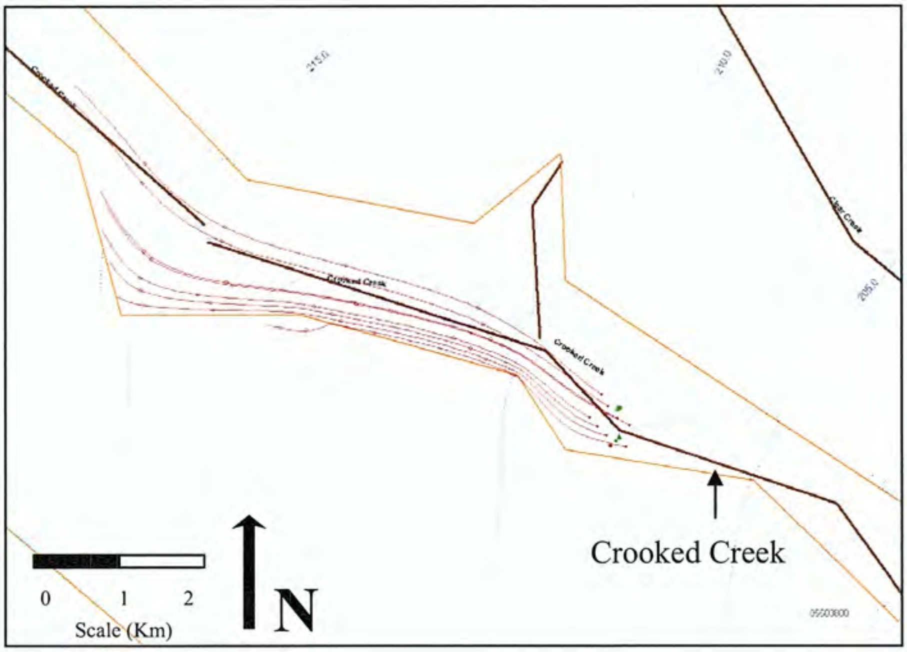


Figure 32. (a) Forward tracking to delineate groundwater watershed (blue zones) of Crooked Creek and Otter Creek, inhomogeneites for alluviums in orange, (b) Source areas of watersheds to the Crooked Creek site calculated by backward particle tracking for 50 years (each time-travel tic represents 10 years)

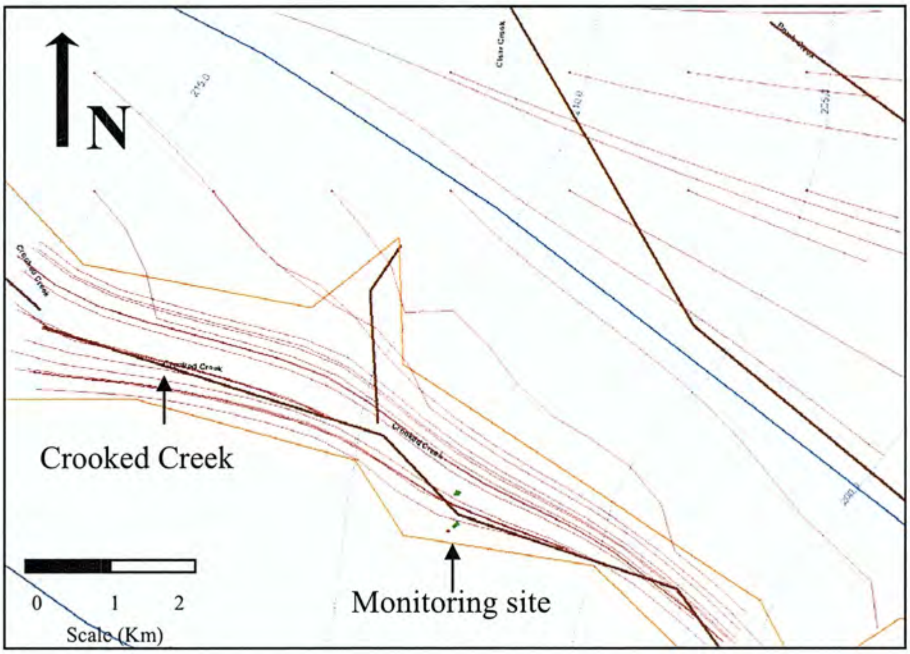


Figure 33. NPS pollutants in groundwater indicating by particle tracking are transported primarily downstream through highly permeable, alluvial channels. This could reduce resistance time and decrease traveling time of pollutants.

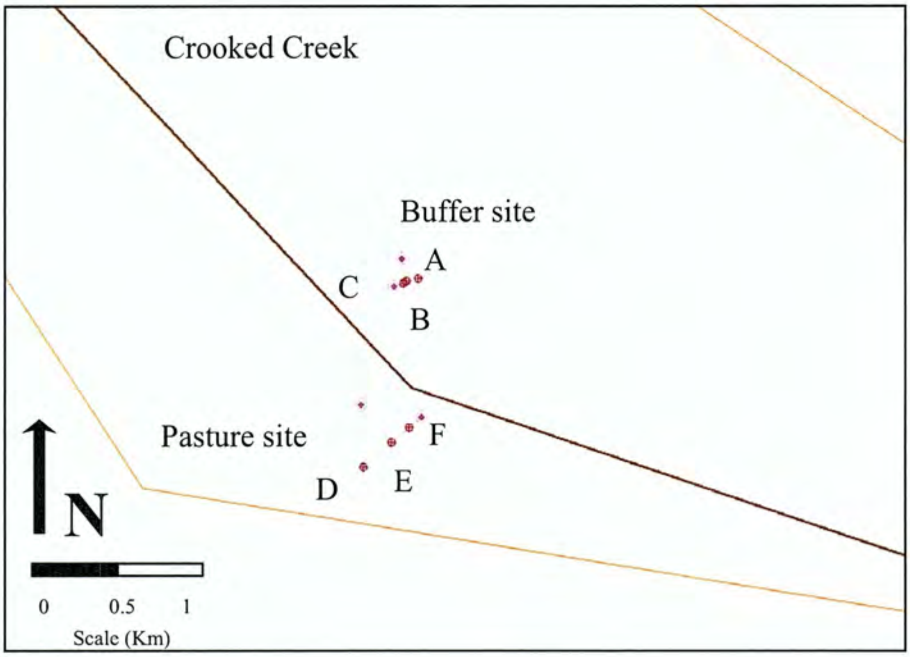


Figure 34. Flux inspectors locate perpendicular to the well nests on both side of Crooked Creek. Each letter represents a well nest and consists of two wells at different depth. Well A10, A15, B13, B18, C13 and C18 are located on the buffer site; Well D15, D17, E9, E14, F11 and F16 are located on the pasture site.

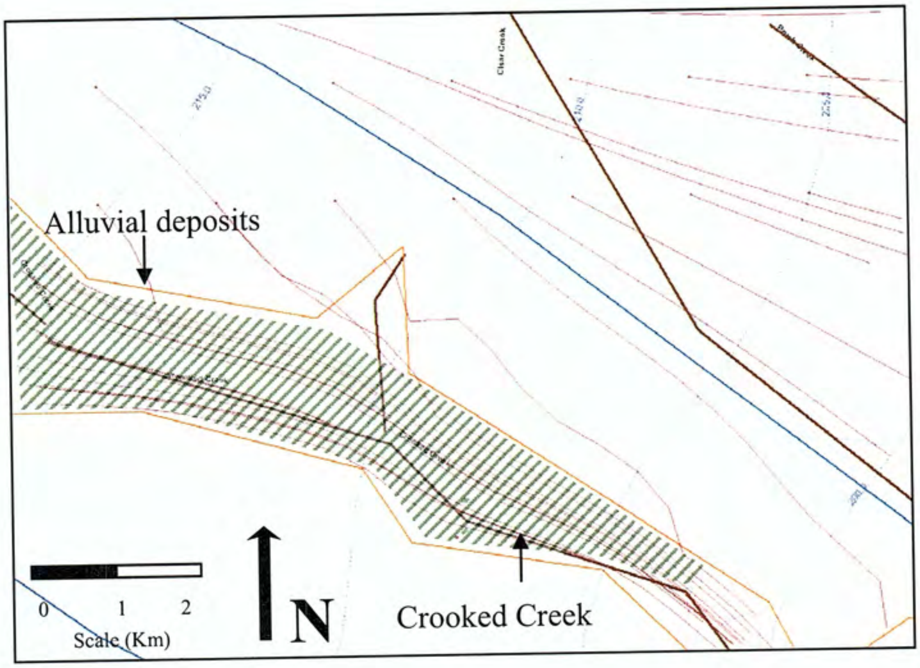


Figure 35. Suggested replacement of riparian buffer settings for northeast Missouri.

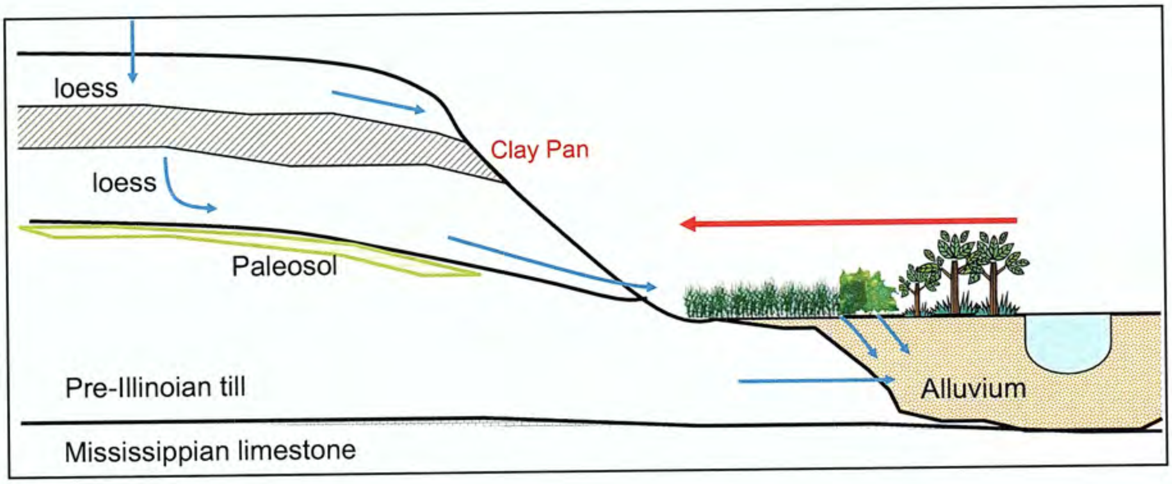


Figure 36. Proposed expansion of buffer from creek to edge of alluvial deposit along the valley.

Table 1. Hydraulic conductivities from soils in the region and slug tests at the Crooked Site.

Study and year	Hydraulic conductivity (m/day)	Test materials
Tindall and Vencill (1995)	0.13 to 0.30 (MSEA site, Management System Evaluation Area; Centralia, MO)	Column studies of claypan soil
Baer and Anderson (1995)	0.03 to 0.16 (MSEA site, Management System Evaluation Area; Centralia, MO)	Saturated soil matrix of claypan soil
Kelly and Pomes (1998)	5.36×10^{-5} to 6.48 (MSEA site, Management System Evaluation Area; Centralia, MO)	Undisturbed clanpan soil cores at three different scale: cylinder of clay, gravity lysimeters, and examination pot
Blanco-Canqui et al. (2002)	0.03 (with bentonite, McCredie, MO) 0.08 (without bentonite, McCredie, MO) 4.41 (without bentonite, Novelty, MO)	Installation of soil monoliths in the field (Depth to claypan)
This study (2005)	3×10^{-3} for limestone bedrock 1.90 for gravel deposits	Slug tests in alluvial channel deposits and limestone bedrock at Crooked Creek site

Table 2. Slug test results from AQTESOLV.

Well	Geology	Falling head (m/day)	Rising head (m/day)
A10	loess/sand	/	/
A15	sand/gravel	0.23	0.31
B13	sand/gravel	/	0.13
B18	sand	1.16	1.53
C13	sand	/	1.62
C18	sandstone/limestone	0.003	/
D15	silt/gravel	1.89	1.90
D17	sandstone/limestone	0.006	/
E9	sand	0.26	0.17
E14	sand/sandstone	0.37	0.37
F11	sand/gravel	/	1.46
F16	gravel/limestone	0.14	0.13

For data and analyses see Appendix A

Table 3. Hydraulic head targets from wells at the Crooked Creek site.

Well number	Easting X	Northing Y	Hydraulic head (m)
A10	582575.6	4384939.9	207.75
A15	582575.5	4384938.2	207.45
B13	582547.0	4384932.7	206.86
B18	582546.5	4384930.8	206.91
C13	582539.9	4384928.6	206.88
C18	582538.3	4384929.1	206.81
D15	582440.2	4384473.5	208.56
D17	582438.5	4384473.5	208.53
E9	582510.4	4384534.3	207.66
E14	582508.9	4384533.3	207.75
F11	582552.9	4384571.4	206.61
F16	582551.3	4384571.7	206.50
Records from 4/2002 to 4/2005; UTM: NAD 83, Zone 15			

Table 4. Input parameters used in the GFLOW model.

Parameter		Initial value
Aquifer base		125 m above mean sea level
Aquifer thickness (allowed to vary depending upon water table elevation)		Up to 200 m
Model horizontal hydraulic conductivity		2 m/day
K value of alluvial inhomogeneity		100 m/day
Model recharge		0.000279 m/day
Near field streams		
	Streambed resistance	0 to 10 days
	Widths	0 to 10 meters
	Depths	0 to 5 meters
Mark Twain Lake		
	Evaptranspiration	0.002745 m/day
	Precipitation	0.002786 m/day
	Lakebed resistance	0.3 days
	Width	100 meters
	Depth	6 meters
Model porosity		0.10
Inhomogeneity porosity		0.25

Table 5. USGS gauging stations used for baseflow separation and model calibration.

County	Site Number	Site Name	From	To
Shelby	05502500	Salt River near Shelbina, MO	10/01/1933	9/30/2004
Monroe	05503800	Crooked Creek near Paris, MO	10/01/1979	9/30/2004
	05506350	Middle Fork Salt River near Holliday, MO	12/17/1998	9/30/2004
	05506800	Elk Fork Salt River near Madison, MO	10/01/1968	9/30/2004
Ralls	05507600	Lick Creek at Perry, MO	10/01/1979	9/30/2004

Table 6. USGS gauging stations used for baseflow separation and BFI results.

County	Site Number	UTM Coordinates		Discharge (m^3/day)	BFI	Baseflow (m^3/day)
		Easting X	Northing Y			
Shelby	05502500	582166.6	4399480.3	870000	0.10	85000
Monroe	05503800	586434.4	4382162.6	153000	0.07	10500
	05506350	574969.6	4375304.2	538000	0.07	39800
	05506800	571621.9	4365361.8	419000	0.07	29300
Ralls	05507600	613940.5	4365486.2	177000	0.08	13300

Table 7. Original calibration target values and values after calibration.

Calibration targets (observed)		Modeled		
		Trial-and-error	**UCODE**	**PEST**
Head targets (m)				
A	207.75	208.15	208.06	208.05
B	206.86	208.18	208.09	208.08
C	206.88	208.18	208.09	208.08
D	208.56	208.10	208.02	208.00
E	207.66	208.39	207.96	207.94
F	206.61	208.00	207.92	207.83
Flux targets (m^3/day)				
05502500	85000	83058	87813	85313
05503800	10500	11829	10005	10248
05506350	39800	37326	40583	39579
05506800	29300	28580	30417	29353
05507600	13300	12607	13247	12735
Stage targets (m)				
05507700	184.90	183.21	183.22	184.98
MTL1	184.92	183.21	183.22	184.98
MTL2	184.92	183.21	183.22	184.98
MTL3	184.91	183.21	183.22	184.98

Table 8. Parameters after calibration using trial-and-error, UCODE and PEST.

Parameter	Initial value	Trial-and-error	UCODE	PEST
Model K	2	5	5.68 (95% CI: 2.42 to 13.3)	5.64
Model R	0.000279	0.000195	0.000210 (95% CI: 0.000151 to 0.000269)	0.000198
Inhomo. K1	100	100	134 (95% CI: 28.3 to 630)	103.58
Inhomo. K2	100	100	100	97.60
Inhomo. K3	100	100	100	98.63
Inhomo. K4	100	100	100	99.93
Inhomo. K5	100	100	100	94.06
Inhomo. K6	100	100	100	97.25
Inhomo. K7	100	100	100	98.40
Inhomo. K8	100	100	100	98.74
Inhomo. K9	100	100	100	94.86
Inhomo. K10	100	100	100	99.97

(Units: m/day)

Table 9. Water balance of Mark Twain Lake from GFLOW.

Category	Inflow (m^3/day)	Outflow (m^3/day)
Ground water	101,000 (11%)	18,000 (2%)
Precipitation	214,000 (22%)	NA
Evapotranspiration	NA	210,000 (22%)
Stream flow	644,000 (67%)	731,000 (76%)
Total	959,000 (100%)	959,000 (100%)

APPENDIX A

Slug Test Data and AQTESOLV Input File

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
A15	0.083	4.6		8	0.6		7	0.55
				23	0.55		35	0.45
				33	0.5		50	0.4
				47	0.45		62	0.35
				64	0.4		83	0.3
				87	0.35		113	0.25
				116	0.3		154	0.2
				151	0.25		220	0.15
				207	0.2		340	0.1
				295	0.15		553	0.05
				402	0.1			

Well	Radius (ft)	Screen length (ft)	Falling	Time (sec)	displacement (ft)	Rising	Time (sec)	displacement (ft)
B13	0.083	4					18	0.56
							28	0.51
							42	0.46
							68	0.41
							104	0.36
							169	0.31
							267	0.26
							403	0.21
							602	0.16
							855	0.11

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
B18	0.083	4		4	0.54		15	0.56
				28	0.34		29	0.36
				36	0.29		35	0.31
				47	0.24		41	0.26
				52	0.19		51	0.21
				65	0.14		62	0.16
				86	0.09		76	0.11
				149	0.04		102	0.06
				427	0			

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
C13	0.083	4					8	0.99
							13	0.89
							17	0.79
							22	0.69
							28	0.59
							34	0.49
							41	0.39
							50	0.29
							62	0.19
							87	0.09
							139	0.04

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
C18	0.083	4		14	0.8			
				305	0.75			
				748	0.72			
				1292	0.7			
				3799	0.61			
				10150	0.44			
				11520	0.42			

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
D15	0.083	4.25		5	1.03		8	0.97
				17	0.58		21	0.57
				22	0.48		25	0.47
				25	0.43		28	0.42
				28	0.38		31	0.37
				33	0.33		35	0.32
				38	0.28		40	0.27
				44	0.23		47	0.22
				54	0.18		53	0.17
				62	0.13		62	0.12
				79	0.08		78	0.07
				146	0.03		108	0.02

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
D17	0.083	2					18	0.19
							83	0.17
							3315	0.14
							5436	0.13

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
E9	0.083	4		8	0.46		12	0.44
				18	0.41		21	0.39
				30	0.21		45	0.34
				43	0.31		82	0.29
				63	0.26		123	0.24
				94	0.21		185	0.19
				154	0.16		263	0.14
				216	0.11		375	0.09
				347	0.06			

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
E14	0.083	4		6	1.12		12	0.93
				16	0.92		23	0.78
				20	0.87		29	0.73
				25	0.82		36	0.68
				32	0.77		44	0.63
				41	0.72		55	0.58
				50	0.67		66	0.53
				61	0.62		82	0.48
				73	0.57		96	0.43
				88	0.52		116	0.38
				102	0.47		140	0.33
				118	0.42		168	0.28
				143	0.37		209	0.23
				168	0.32		248	0.18
				197	0.27		313	0.13
				234	0.22		425	0.08
				285	0.17			
				351	0.12			

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
F11	0.083	4					6	0.39
							14	0.34
							24	0.24
							32	0.19
							43	0.14
							65	0.09
							107	0.04

Well	Radius (ft)	Screen length (ft)	***Falling***	Time (sec)	displacement (ft)	***Rising***	Time (sec)	displacement (ft)
F16	4	0.083		8	0.54		16	0.43
				43	0.44		19	0.41
				83	0.39		52	0.36
				125	0.34		104	0.31
				180	0.29		155	0.26
				234	0.24		222	0.21
				304	0.19		328	0.16
				392	0.14		471	0.11
				524	0.09			

APPENDIX B

ArcView Transcript File
(Abstract)

```
/3.1
(Extension.1
      Name: "Give me points"
      Dependencies:     "$AVBIN/avdlog.dll\n"
      FirstRootClassName:     "Choice"
      Roots:      2
      Roots:      3
      Roots:      147
      Roots:      148
      Roots:      149
      Roots:      150
      Roots:      151
      Roots:      152
      Roots:      153
      Roots:      154
      Roots:      155
      Roots:      156
      Roots:      157
      Roots:      158
      Roots:      159
      Roots:      160
      Version:    31
      About:      "Give me points (v 1.0)"
      InstallScript:    161
      UninstallScript:  162
      ExtVersion: 1
)

(Choice.2
      Disabled:   1
      Help: "Opens the \"Give me points\" Wizard."
      Update:     "View.HasDataUpdate"
      Label:      "Give me points..."
      Click:      "GMP.Open"
      Shortcut:   "Keys.None"
)

(AVDLog.3
      Name: "GMP.dlg"
      X:    41
      Y:    44
      W:    281
      H:    168
      ConstrainedControlNames:      4
      ConstrainedControlNames:      5
      ConstrainedControlNames:      6
      ConstrainedControlNames:      7
      ConstrainedControlNames:      8
      ConstrainedControlNames:      9
      ConstrainedControlNames:      10
      ConstrainedControlNames:      11
      Constraints:      12
      Constraints:      13
      Constraints:      14
      Constraints:      15
```

```
        Constraints:      16
        Constraints:      17
        Constraints:      18
        Constraints:      19
        Server:     20
        ControlPanel:     21
        ObjectTag:  20
        Title:      "Give me points"
        AlwaysOnTop:      1
        HasTitleBar:      1
        Closeable:  1
        DefaultButton:    146
)

(AVStr.4
        S:    "cmdBack"
)

(AVStr.5
        S:    "cmdNext"
)

(AVStr.6
        S:    "cmdOk"
)

(AVStr.7
        S:    "cmdAbout"
)

(AVStr.8
        S:    "cmdFile"
)

(AVStr.9
        S:    "lstColor"
)

(AVStr.10
        S:    "cmdClear"
)

(AVStr.11
        S:    "cmdSelect"
)

(Numb.12
        N:    85.00000000000000
)

(Numb.13
        N:    85.00000000000000
)

(Numb.14
```

```
      N:    85.00000000000000
)

(Numb.15
      N:    85.00000000000000
)

(Numb.16
      N:    85.00000000000000
)

(Numb.17
      N:    85.00000000000000
)

(Numb.18
      N:    85.00000000000000
)

(Numb.19
      N:    85.00000000000000
)

(Nil.20
)

(CPanel.21
      Child:        22
      Child:        73
      Child:        101
      Child:        112
      Child:        113
      Child:        114
      Child:        115
      Child:        134
      Child:        135
      ResBox:       137
      ResBox:       138
      ResBox:       139
      ResBox:       140
      ResBox:       141
      ResBox:       142
      ResBox:       143
      ResBox:       144
      ResBox:       145
      Listening:    1
```

(The script here only shows part of the original, original script has lines over 100 pages)

http://arcscripts.esri.com/details.asp?dbid=13300

APPENDIX C

UCODE Input File

```
#########################################
#####  UCODE Universal Input File   #####
#####                              #####
#####    Written by GFLOW          #####
#####         03/16/06             #####
#########################################
         3          # PHASE
##### Sensitivity and Regression Control
         2          # DIFFERENCING
  0.010000          # TOL
  0.000100          # SOSR
         0          # NOPT
        10          # MAX-ITER
  2.00000           # MAX-CHANGE
##### Inversion Code and Application Models
mrdrive             # INVERSION ALGORITHM
         1          # N-APPLICATIONS
G-UCODE.bat           # APPLICATION MODEL EXECUTION COMMAND
##### Printing Options
         1          # SCALE-SENSITIVITIES
         1          # PRINT-INTERMEDIATE
         1          # GRAPH
         0          # NUMBER-RESIDUAL-SETS
#
##############################################################
##                      Head targets                        ##
##############################################################
#
###################### Observation Data #####################
# OBS-NAME   OBS-VALUE   STATISTIC   STAT-FLAG   PLOT-SYMBOL #
##############################################################
#
A    0207.75     2.000000       1       1#       TP_000786
B    0206.86     2.000000       1       1#       TP_000787
C    0206.88     2.000000       1       1#       TP_000788
D    0208.56     2.000000       1       1#       TP_000789
E    0207.66     2.000000       1       1#       TP_000790
F    0206.61     2.000000       1       1#       TP_000791
##############################################################
##                  Stream Flow targets                     ##
##############################################################
#
###################### Observation Data #####################
# OBS-NAME   OBS-VALUE   STATISTIC   STAT-FLAG   PLOT-SYMBOL #
##############################################################
#
5503800f   10500.00     0.200000       2       2#       TG_000979
5506350f   39800.00     0.200000       2       2#       TG_000981
5506800f   29300.00     0.200000       2       2#       TG_000982
5502500f   85300.00     0.200000       2       2#       TG_000984
5507600f   13300.00     0.200000       2       2#       TG_000985
##############################################################
##                  Lake Stage targets                      ##
##############################################################
#
###################### Observation Data #####################
# OBS-NAME   OBS-VALUE   STATISTIC   STAT-FLAG   PLOT-SYMBOL #
##############################################################

#
MTL1    0184.92     1.000000       1       3#       TS_001657
MTL2    0184.92     1.000000       1       3#       TS_001658
MTL3    0184.91     1.000000       1       3#       TS_001659
05507700    0184.90     1.000000       1       3#       TS_001660
END
```

APPENDIX D

UCODE Output File

```
******************************************************************
             UCODE VERSION 3.02 (OCTOBER 2000)
             Documented in: USGS WRI98-4080
          by Eileen P. Poeter and Mary C. Hill
    UPDATES can be obtained from http://water.usgs.gov/
           OR from http://www.mines.edu/igwmc/freeware/ucode
******************************************************************


ECHO OF INPUT

DOS or MS-Windows PLATFORM

PHASE SELECTED ...................................................... 22
____________________
REGRESSION CONTROLS:

     SENSITIVITY DIFFERENCING (1=FORWARD, 2= CENTRAL) ............... 2
     PARAMETER ESTIMATION CONVERGES WHEN EITHER OF THE
                          FOLLOWING IS SATISFIED:
       1) MAXIMUM FRACTIONAL PARAMETER CHANGE IS LESS THAN .......... 0.010000
       2) SUM-OF-SQUARED WEIGHTED RESIDUALS DIFFERS OVER
             THREE ITERATIONS BY LESS THAN A FACTOR OF: ............ 0.000100
     IF THE PARAMETER CHANGE VECTOR DIVERGES BY GREATER THAN ........ 85
                   DEGREES FROM THE DOWN GRADIENT DIRECTION
                       THE MARQUARDT PARAMETER WILL BE USED
     THE MARQUARDT FACTOR WILL BE ................................... 1.5
     THE MARQUARDT INCREMENT WILL BE ................................ 0.001
     OPTIONAL QUASI-NEWTON UPDATING (0= NO 1=YES) ................... 0
     MAXIMUM NUMBER OF PARAMETER ITERATIONS BEFORE TERMINATION ...... 24
     MAXIMUM ALLOWABLE FRACTIONAL PARAMETER CHANGE .................. 2.0

     NAME OF INVERSION ALGORITHM IS         mrdrive

     NUMBER OF APPLICATION CODES TO RUN IS .......................... 1
          CODE NAME                        G-UCODE.bat

__________________
PRINTING CONTROLS:

     SENSITIVITY SCALING (0=NO-SCALING 1=DIMENSIONLESS 2=1% 3= 1&2) . 1
     INTERMEDIATE PRINTING (0=NONE, 1= PRINT) ....................... 1
     PRODUCE GRAPHING AND POSTPROCESSING FILES (0=NO, 1=YES) ........ 1
     # OF RESIDUAL SETS FOR EVALUATION OF APPARENT NON-RANDOMNESS ... 0

________________________
OBSERVATION INFORMATION:

 NUMBER OF OBSERVATIONS = 15

 OBS#    OBSERVATION ID        VALUE              STAT    STAT      SQRT       PLOT
                                                          TYPE    WEIGHT     SYMBOL

    1                 A       207.75                 2    STD         0.5          1
    2                 B       206.86                 2    STD         0.5          1
    3                 C       206.88                 2    STD         0.5          1
    4                 D       208.56                 2    STD         0.5          1
    5                 E       207.66                 2    STD         0.5          1
    6                 F       206.61                 2    STD         0.5          1
    7          5503800f        10500               0.2     CV   0.0004762          2
    8          5506350f        39800               0.2     CV   0.0001256          2
```

9	5506800f	29300	0.2	CV	0.0001706	2
10	5502500f	85300	0.2	CV	5.862e-005	2
11	5507600f	13300	0.2	CV	0.0003759	2
12	MTL1	184.92	1	STD	1	3
13	MTL2	184.92	1	STD	1	3
14	MTL3	184.91	1	STD	1	3
15	05507700	184.9	1	STD	1	3

PARAMETER INFORMATION:

INITIAL INFORMATION FOR 12 PARAMETERS

PARAMETER NAME	INITIAL VALUE	REASONABLE MINIMUM	REASONABLE MAXIMUM	PERTURBATION FRACTIONAL AMOUNT	LOG TRANS FLAG	ESTIMATE FLAG
AreaK_____	5	0.5	50	0.01	YES	YES
Am1_______	100	10	1000	0.01	YES	YES
Am10______	100	10	1000	0.01	YES	YES
Am2_______	100	10	1000	0.01	YES	YES
Am3_______	100	10	1000	0.01	YES	YES
Am4_______	100	10	1000	0.01	YES	YES
Am5_______	100	10	1000	0.01	YES	YES
Am6_______	100	10	1000	0.01	YES	YES
Am7_______	100	10	1000	0.01	YES	YES
Am8_______	100	10	1000	0.01	YES	YES
Am9_______	100	10	1000	0.01	YES	YES
AreaRech__	0.000195	1.95e-005	0.00195	0.01	NO	YES

FUNCTION INFORMATION:

Functions are used for parameter AreaRech____ in file Bilrev10.tpl

Parameter <AreaRech____> is MANIPULATED by a function 1 times in file Bilrev10.tpl

TEMPLATE PARAMETER INFORMATION:

Analyzing Parameter IDs in file: {Bilrev10.tpl}
{12} lines out of {1904} include Parameter IDs for substitution
the last line with a substitution is {265}
Parameter ID: {!AreaK_______!} occurs: {1} times in the template file
Parameter ID: {!AreaRech____!} occurs: {1} times in the template file
Parameter ID: {!Am1_________!} occurs: {1} times in the template file
Parameter ID: {!Am2_________!} occurs: {1} times in the template file
Parameter ID: {!Am4_________!} occurs: {1} times in the template file
Parameter ID: {!Am5_________!} occurs: {1} times in the template file
Parameter ID: {!Am6_________!} occurs: {1} times in the template file
Parameter ID: {!Am7_________!} occurs: {1} times in the template file
Parameter ID: {!Am8_________!} occurs: {1} times in the template file
Parameter ID: {!Am9_________!} occurs: {1} times in the template file

```
Parameter ID: {!Am3________!} occurs: {1} times in the template file
Parameter ID: {!Am10_______!} occurs: {1} times in the template file

***************************************************

    EXECUTING MRDRIVE VERSION 1.08  (NOV 1998)

***************************************************



 OBSERVATIONS

       OBSERVATION    MEASURED  SIMULATED                              WEIGHTED
 OBS#      NAME       VALUE      VALUE        RESIDUAL  WEIGHT**.5   RESIDUAL

    1 A               207.750     208.150    -0.4002    0.500     -0.2001
    2 B               206.860     208.177     -1.317    0.500     -0.6583
    3 C               206.880     208.182     -1.302    0.500     -0.6509
    4 D               208.560     208.104     0.4561    0.500      0.2281
    5 E               207.660     208.041    -0.3808    0.500     -0.1904
    6 F               206.610     208.002     -1.392    0.500     -0.6962
    7 5503800f        10500.0     11826.7     -1327.    4.762E-04-0.6318
    8 5506350f        39800.0     37308.4      2492.    1.256E-04 0.3130
    9 5506800f        29300.0     28581.2      718.8    1.706E-04 0.1227
   10 5502500f        85300.0     83054.6      2245.    5.862E-05 0.1316
   11 5507600f        13300.0     12602.7      697.3    3.759E-04 0.2621
   12 MTL1            184.920     183.197      1.723     1.00        1.723
   13 MTL2            184.920     183.197      1.723     1.00        1.723
   14 MTL3            184.910     183.197      1.713     1.00        1.713
   15 05507700        184.900     183.197      1.703     1.00        1.703

 STATISTICS FOR THESE RESIDUALS :
 MAXIMUM WEIGHTED RESIDUAL  : 0.172E+01 OBS#     12 MTL1
 MINIMUM WEIGHTED RESIDUAL  :-0.696E+00 OBS#      6 F
 AVERAGE WEIGHTED RESIDUAL  : 0.326E+00
 # RESIDUALS >= 0. :       9
 # RESIDUALS < 0.  :       6
 NUMBER OF RUNS  :    4  IN   15 OBSERVATIONS

 SUM OF SQUARED WEIGHTED RESIDUALS           13.835

 SUM OF SQUARED WEIGHTED RESIDUALS (WITH PRIOR)  13.835

 STATISTICS FOR ALL RESIDUALS :
 AVERAGE WEIGHTED RESIDUAL  : 0.326E+00
 # RESIDUALS >= 0. :       9
 # RESIDUALS < 0.  :       6
 NUMBER OF RUNS  :    4  IN   15 OBSERVATIONS

 INTERPRETTING THE CALCULATED RUNS STATISTIC VALUE OF      -2.07
 NOTE: THE FOLLOWING APPLIES ONLY IF
        # RESIDUALS >= 0. IS > 10 AND
        # RESIDUALS <  0. IS > 10
 THE NEGATIVE VALUE MAY INDICATE TOO FEW RUNS:
    IF THE VALUE IS < -1.28 , THERE IS < 10% CHANCE THE VALUES ARE RANDOM,
    IF THE VALUE IS < -1.645, THERE IS < 5% CHANCE THE VALUES ARE RANDOM,
    IF THE VALUE IS < -1.96 , THERE IS < 2.5% CHANCE THE VALUES ARE RANDOM
```

DIMENSIONLESS SCALED SENSITIVITIES (SCALED BY (PARAMETER_VALUE*(wt**.5))

PARAMETER #:	1	2	3	4	5	6
PARAMETER ID:	AreaK	Am1	Am10	Am2	Am3	Am4
OBS# OBS ID						
1 A	-6.75E-01	-6.04E-01	4.04E-02	-1.84E-01	-1.39E-01	-2.48E-01
2 B	-6.75E-01	-6.08E-01	4.22E-02	-1.86E-01	-1.39E-01	-2.49E-01
3 C	-6.75E-01	-6.08E-01	4.22E-02	-1.84E-01	-1.41E-01	-2.48E-01
4 D	-6.86E-01	-6.04E-01	4.22E-02	-1.84E-01	-1.41E-01	-2.53E-01
5 E	-6.80E-01	-5.76E-01	4.22E-02	-1.86E-01	-1.41E-01	-2.46E-01
6 F	-6.77E-01	-5.57E-01	4.22E-02	-1.86E-01	-1.41E-01	-2.46E-01
7 5503800f	-9.65E+00	-1.96E+01	-7.01E-02	-1.86E-01	2.72E-01	-6.25E+00
8 5506350f	1.90E+00	-3.07E-01	-1.40E-01	4.79E-01	4.66E-01	-1.84E+00
9 5506800f	1.72E+00	-7.52E-03	6.29E-03	-2.28E-02	-2.16E-02	9.82E-03
10 5502500f	1.48E+00	-5.49E-01	-1.03E-02	-1.59E+00	7.33E+00	-2.80E-01
11 5507600f	-2.40E+00	9.87E-02	-6.84E-02	2.20E-01	2.15E-01	-1.13E-01
12 MTL1	4.79E-02	0.00E+00	0.00E+00	0.00E+00	4.57E-02	0.00E+00
13 MTL2	4.79E-02	0.00E+00	0.00E+00	0.00E+00	4.57E-02	0.00E+00
14 MTL3	4.79E-02	0.00E+00	0.00E+00	0.00E+00	4.57E-02	0.00E+00
15 05507700	4.79E-02	0.00E+00	0.00E+00	0.00E+00	4.57E-02	0.00E+00

COMPOSITE SCALED SENSITIVITIES
((SUM OF THE SQUARED VALUES)/ND)**.5

PARAMETER #:	1	2	3	4	5	6
PARAMETER ID:	AreaK	Am1	Am10	Am2	Am3	Am4
	2.71	5.09	5.151E-02	0.451	1.90	1.69

DIMENSIONLESS SCALED SENSITIVITIES (SCALED BY (PARAMETER_VALUE*(wt**.5))

PARAMETER #:	7	8	9	10	11	12
PARAMETER ID:	Am5	Am6	Am7	Am8	Am9	AreaRech
OBS# OBS ID						
1 A	-1.05E-02	4.22E-02	0.00E+00	0.00E+00	2.27E-01	1.21E+00
2 B	-1.23E-02	4.22E-02	1.76E-03	1.76E-03	2.27E-01	1.21E+00
3 C	-1.05E-02	4.22E-02	1.76E-03	1.76E-03	2.27E-01	1.21E+00
4 D	-1.05E-02	4.22E-02	1.76E-03	1.76E-03	2.28E-01	1.22E+00
5 E	-1.05E-02	4.22E-02	1.76E-03	1.76E-03	2.28E-01	1.21E+00
6 F	-1.05E-02	4.22E-02	1.76E-03	1.76E-03	2.28E-01	1.20E+00
7 5503800f	-2.69E-01	-7.24E-02	-1.18E-03	-1.07E-03	-3.41E-01	1.59E+01
8 5506350f	-5.02E+00	-2.19E-01	-9.27E-03	-3.28E-03	-7.32E-01	3.67E+00
9 5506800f	-5.43E-02	5.64E+00	-7.90E-02	0.00E+00	3.22E-02	2.32E+00
10 5502500f	-1.96E-02	-1.35E-02	1.37E-03	-1.05E-04	7.70E-03	2.57E+00
11 5507600f	0.00E+00	-6.58E-02	2.62E-03	6.31E-02	-1.17E+00	5.71E+00
12 MTL1	0.00E+00	6.68E-02	2.46E-02	9.13E-02	0.00E+00	2.40E-01
13 MTL2	0.00E+00	6.68E-02	2.46E-02	9.13E-02	0.00E+00	2.40E-01
14 MTL3	0.00E+00	6.68E-02	2.46E-02	9.13E-02	0.00E+00	2.40E-01
15 05507700	0.00E+00	6.68E-02	2.46E-02	9.13E-02	0.00E+00	2.40E-01

COMPOSITE SCALED SENSITIVITIES
((SUM OF THE SQUARED VALUES)/ND)**.5

PARAMETER #:	7	8	9	10	11	12
PARAMETER ID:	Am5	Am6	Am7	Am8	Am9	AreaRech

1.30 1.46 2.418E-02 4.993E-02 0.394 4.61

SUMMARY OF SCALED COMPOSITE SENSITIVITIES FOR ALL PARAMETERS

COMPOSITE SCALED SENSITIVITIES
((SUM OF THE SQUARED VALUES)/ND)**.5

PARAMETER #:	1	2	3	4	5	6
PARAMETER ID:	AreaK	Am1	Am10	Am2	Am3	Am4
	2.71	5.09	5.151E-02	0.451	1.90	1.69

PARAMETER #:	7	8	9	10	11	12
PARAMETER ID:	Am5	Am6	Am7	Am8	Am9	AreaRech
	1.30	1.46	2.418E-02	4.993E-02	0.394	4.61

COVARIANCE MAT.

	1	2	3	4	5	6
	7	8	9	10	11	12
1	65.75	-31.95	2019.	-10.24	-60.21	-75.12
	1.1722E+02	-6.3668E+01	1.0193E+03	-4.2683E+02	-2.8078E+02	2.1559E-03
2	-31.95	148.8	-4666.	35.31	11.79	-248.2
	1.0797E+02	4.5206E+01	1.7225E+03	-5.2624E+02	5.9974E+02	1.0695E-03
3	2019.	-4666.	6.9498E+05	5.3531E+04	1.2186E+04	-1.0144E+04
	-1.1940E+03	-3.6892E+01	1.5523E+04	-3.2313E+03	-5.9913E+04	-1.7278E-01
4	-10.24	35.31	5.3531E+04	1.5458E+04	3284.	-27.87
	2.5654E+02	-1.8419E+02	-1.3431E+03	-2.2463E+03	2.4539E+03	1.8355E-02
5	-60.21	11.79	1.2186E+04	3284.	767.4	11.44
	-8.1467E+01	7.2253E+00	-3.1499E+03	5.4832E+02	4.2950E+02	5.4787E-05
6	-75.12	-248.2	-1.0144E+04	-27.87	11.44	1511.
	-4.6156E+02	6.4274E+01	4.2030E+03	-1.4375E+03	1.4469E+03	5.7276E-03
7	117.2	108.0	-1194.	256.5	-81.47	-461.6
	4.3490E+02	-1.8552E+02	-1.4087E+03	-6.2043E+01	2.9112E+02	7.1199E-03
8	-63.67	45.21	-36.89	-184.2	7.225	64.27
	-1.8552E+02	1.0203E+03	6.7282E+04	-1.8631E+04	-7.8160E+02	-1.8443E-03
9	1019.	1722.	1.5523E+04	-1343.	-3150.	4203.
	-1.4087E+03	6.7282E+04	5.0032E+06	-1.4079E+06	-5.1380E+04	2.1726E-01
10	-426.8	-526.2	-3231.	-2246.	548.3	-1438.
	-6.2043E+01	-1.8631E+04	-1.4079E+06	4.0048E+05	1.2653E+04	-8.0650E-02
11	-280.8	599.7	-5.9913E+04	2454.	429.5	1447.
	2.9112E+02	-7.8160E+02	-5.1380E+04	1.2653E+04	1.0177E+04	3.3804E-02
12	2.1559E-03	1.0695E-03	-0.1728	1.8355E-02	5.4787E-05	5.7276E-03
	7.1199E-03	-1.8443E-03	2.1726E-01	-8.0650E-02	3.3804E-02	3.2350E-07

PARAMETER SUMMARY

PARAMETER VALUES IN "REGRESSION" SPACE --- LOG TRANSFORMED AS APPLICABLE

PARAMETER #:	1	2	3	4	5
PARAMETER ID:	AreaK	Am1	Am10	Am2	Am3
* = LOG TRNS:	*	*	*	*	*
UPPER 95% C.I.	1.19E+01	1.89E+01	1.15E+03	1.74E+02	4.03E+01
FINAL VALUES	6.99E-01	2.00E+00	2.00E+00	2.00E+00	2.00E+00
LOWER 95% C.I.	-1.05E+01	-1.49E+01	-1.15E+03	-1.70E+02	-3.63E+01
STD. DEV.	3.52E+00	5.30E+00	3.62E+02	5.40E+01	1.20E+01
COEF. OF VAR. * if value=0	5.04E+00	2.65E+00	1.81E+02	2.70E+01	6.02E+00

PARAMETER VALUES IN "REGRESSION" SPACE --- LOG TRANSFORMED AS APPLICABLE

PARAMETER #:	6	7	8	9	10
PARAMETER ID:	Am4	Am5	Am6	Am7	Am8
* = LOG TRNS:	*	*	*	*	*
UPPER 95% C.I.	5.57E+01	3.08E+01	4.61E+01	3.09E+03	8.77E+02
FINAL VALUES	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00
LOWER 95% C.I.	-5.17E+01	-2.68E+01	-4.21E+01	-3.09E+03	-8.73E+02
STD. DEV.	1.69E+01	9.06E+00	1.39E+01	9.71E+02	2.75E+02
COEF. OF VAR. * if value=0	8.44E+00	4.53E+00	6.94E+00	4.86E+02	1.37E+02

PARAMETER VALUES IN "REGRESSION" SPACE --- LOG TRANSFORMED AS APPLICABLE

PARAMETER #:	11	12
PARAMETER ID:	Am9	AreaRech
* = LOG TRNS:	*	
UPPER 95% C.I.	1.41E+02	2.00E-03
FINAL VALUES	2.00E+00	1.95E-04
LOWER 95% C.I.	-1.37E+02	-1.61E-03
STD. DEV.	4.38E+01	5.69E-04
COEF. OF VAR. * if value=0	2.19E+01	2.92E+00

PHYSICAL PARAMETER VALUES --- EXP10 OF LOG TRANSFORMED PARAMETERS

PARAMETER #:	1	2	3	4	5
PARAMETER ID:	AreaK	Am1	Am10	Am2	Am3
* = LOG TRNS:	*	*	*	*	*

```
 UPPER 95% C.I.      8.03E+11   7.18E+18 ********** ********** **********
 FINAL VALUES        5.00E+00   1.00E+02   1.00E+02   1.00E+02   1.00E+02
 LOWER 95% C.I.      3.11E-11   1.39E-15   0.00E+00   0.00E+00   5.22E-37

     REASONABLE
   UPPER LIMIT       5.00E+01   1.00E+03   1.00E+03   1.00E+03   1.00E+03
     REASONABLE
   LOWER LIMIT       5.00E-01   1.00E+01   1.00E+01   1.00E+01   1.00E+01

ESTIMATE ABOVE (1)
 BELOW(-1)LIMITS        0          0          0          0          0
ENTIRE CONF. INT.
 ABOVE(1)BELOW(-1)      0          0          0          0          0
 ------------------------------------------------------------------------

 PHYSICAL PARAMETER VALUES --- EXP10 OF LOG TRANSFORMED PARAMETERS
 ------------------------------------------------------------------------

 PARAMETER #:           6          7          8          9         10
 PARAMETER ID:       Am4_______ Am5_______ Am6_______ Am7_______ Am8_______
 * = LOG TRNS:       *          *          *          *          *

 UPPER 95% C.I.      **********   6.59E+30 ********** ********** **********
 FINAL VALUES        1.00E+02   1.00E+02   1.00E+02   1.00E+02   1.00E+02
 LOWER 95% C.I.      0.00E+00   1.52E-27   7.22E-43   0.00E+00   0.00E+00

     REASONABLE
   UPPER LIMIT       1.00E+03   1.00E+03   1.00E+03   1.00E+03   1.00E+03
     REASONABLE
   LOWER LIMIT       1.00E+01   1.00E+01   1.00E+01   1.00E+01   1.00E+01

ESTIMATE ABOVE (1)
 BELOW(-1)LIMITS        0          0          0          0          0
ENTIRE CONF. INT.
 ABOVE(1)BELOW(-1)      0          0          0          0          0
 ------------------------------------------------------------------------

 PHYSICAL PARAMETER VALUES --- EXP10 OF LOG TRANSFORMED PARAMETERS
 ------------------------------------------------------------------------

 PARAMETER #:          11         12
 PARAMETER ID:       Am9_______ AreaRech__
 * = LOG TRNS:       *

 UPPER 95% C.I.      **********   2.00E-03
 FINAL VALUES        1.00E+02   1.95E-04
 LOWER 95% C.I.      0.00E+00  -1.61E-03

     REASONABLE
   UPPER LIMIT       1.00E+03   1.95E-03
     REASONABLE
   LOWER LIMIT       1.00E+01   1.95E-05

ESTIMATE ABOVE (1)
 BELOW(-1)LIMITS        0          0
ENTIRE CONF. INT.
 ABOVE(1)BELOW(-1)      0          0


          ----------------
```

CORRELATION MAT.

	1	2	3	4	5	6	7	8	9	10	11	12
1	1.000	-0.3230	0.2987	-1.0153E-02	-0.2680	-0.2383	6.9318E-01	-2.4581E-01	5.6199E-02	-8.3179E-02	-3.4325E-01	4.6745E-01
2	-0.3230	1.000	-0.4588	2.3287E-02	3.4902E-02	-0.5234	4.2448E-01	1.1603E-01	6.3133E-02	-6.8175E-02	4.8740E-01	1.5415E-01
3	0.2987	-0.4588	1.000	0.5165	0.5276	-0.3131	-6.8677E-02	-1.3854E-03	8.3246E-03	-6.1249E-03	-7.1241E-01	-3.6439E-01
4	-1.0153E-02	2.3287E-02	0.5165	1.000	0.9535	-5.7675E-03	9.8942E-02	-4.6379E-02	-4.8295E-03	-2.8550E-02	1.9565E-01	2.5956E-01
5	-0.2680	3.4902E-02	0.5276	0.9535	1.000	1.0620E-02	-1.4102E-01	8.1653E-03	-5.0835E-02	3.1277E-02	1.5369E-01	3.4772E-03
6	-0.2383	-0.5234	-0.3131	-5.7675E-03	1.0620E-02	1.000	-5.6940E-01	5.1767E-02	4.8341E-02	-5.8440E-02	3.6898E-01	2.5907E-01
7	0.6932	0.4245	-6.8677E-02	9.8942E-02	-0.1410	-0.5694	1.0000E+00	-2.7851E-01	-3.0199E-02	-4.7012E-03	1.3838E-01	6.0026E-01
8	-0.2458	0.1160	-1.3854E-03	-4.6379E-02	8.1653E-03	5.1767E-02	-2.7851E-01	1.0000E+00	9.4170E-01	-9.2167E-01	-2.4256E-01	-1.0151E-01
9	5.6199E-02	6.3133E-02	8.3246E-03	-4.8295E-03	-5.0835E-02	4.8341E-02	-3.0199E-02	9.4170E-01	1.0000E+00	-9.9461E-01	-2.2770E-01	1.7077E-01
10	-8.3179E-02	-6.8175E-02	-6.1249E-03	-2.8550E-02	3.1277E-02	-5.8440E-02	-4.7012E-03	-9.2167E-01	-9.9461E-01	1.0000E+00	1.9820E-01	-2.2407E-01
11	-0.3433	0.4874	-0.7124	0.1956	0.1537	0.3690	1.3838E-01	-2.4256E-01	-2.2770E-01	1.9820E-01	1.0000E+00	5.8916E-01
12	0.4675	0.1542	-0.3644	0.2596	3.4772E-03	0.2591	6.0026E-01	-1.0151E-01	1.7077E-01	-2.2407E-01	5.8916E-01	1.0000E+00

THE CORRELATION OF THE FOLLOWING PARAMETER PAIRS >= .95

PARAMETER #	ID	#	ID	CORRELATION
4	Am2	5	Am3	0.95
9	Am7	10	Am8	-0.99

THE CORRELATION OF THE FOLLOWING PARAMETER PAIRS IS BETWEEN .90 AND .95

PARAMETER #	ID	#	ID	CORRELATION
8	Am6	9	Am7	0.94
8	Am6	10	Am8	-0.92

THE CORRELATION OF THE FOLLOWING PARAMETER PAIRS IS BETWEEN .85 AND .90

PARAMETER #	ID	#	ID	CORRELATION

CORRELATIONS GREATER THAN 0.95 COULD INDICATE THAT THERE IS NOT ENOUGH INFORMATION IN THE OBSERVATIONS AND PRIOR USED IN THE REGRESSION TO ESTIMATE PARAMETER VALUES INDIVIDUALLY.
TO CHECK THIS, START THE REGRESSION FROM SETS OF INITIAL PARAMETER VALUES THAT DIFFER BY MORE THAT TWO STANDARD DEVIATIONS FROM THE ESTIM ATED VALUES. IF THE RESULTING ESTIMATES ARE WELL WITHIN ONE STANDARD DEVIATION OF THE PREVIOUSLY ESTIMATED VALUE, THE ESTIMATES ARE PROBABLY DETERMINED INDEPENDENTLY WITH THE OBSERVATIONS AND PRIOR USED IN THE REGRESSION. OTHERWISE, YOU MAY ONLY BE ESTIMATING THE RATIO OR SUM OF THE HIGHLY CORRELATED PARAMETERS.
FOR UCODE, THE INITIAL PARAMETER VALUES ARE IN THE PREPARE FILE.

```
LEAST-SQUARES OBJ FUNC (DEP.VAR. ONLY)- =  13.835
LEAST-SQUARES OBJ FUNC (W/PARAMETERS)-- =  13.835
CALCULATED ERROR VARIANCE-------------- =  4.6116
STANDARD ERROR OF THE REGRESSION------- =  2.1475
```

```
 CORRELATION COEFFICIENT---------------- = 0.99995
      W/PARAMETERS---------------------- = 0.99995
 ITERATIONS----------------------------- =       1

      MAX LIKE OBJ FUNC =  135.60
      AIC STATISTIC---- =  159.60
      BIC STATISTIC---- =  168.09

ORDERED DEPENDENT-VARIABLE WEIGHTED RESIDUALS
NUMBER OF RESIDUALS INCLUDED:          15
 -0.696       -0.658       -0.651       -0.632       -0.200       -0.190
  0.123        0.132        0.228        0.262        0.313         1.70
   1.71         1.72         1.72
CORRELATION BETWEEN ORDERED WEIGHTED RESIDUALS
                                       AND NORMAL ORDER STATISTICS =     0.841
     (CALCULATED USING EQ.38 OF HILL,1992 OR EQ.23 OF HILL,1998)

-------------------------------------------------------------------------
COMMENTS ON THE INTERPRETATION OF THE CORRELATION BETWEEN
WEIGHTED RESIDUALS AND NORMAL ORDER STATISTICS:

Generally, IF the reported CORRELATION is LESS than the critical value,
at the selected significance level (usually 5 or 10%), the hypothesis
that the weighted residuals are INDEPENDENT AND NORMALLY DISTRIBUTED
would be REJECTED.  HOWEVER, in this case, conditions are outside of
the range of published critical values as discussed below.

The sum of the number of observations and prior information items is    15
which is less than 35, the minimum value for which critical values are
published.  Therefore, the critical values for the 5 and 10% significance
levels are less than 0.943 and 0.952, respectively.

CORRELATIONS GREATER than these critical values indicate that, probably, the
weighted residuals ARE INDEPENDENT AND NORMALLY DISTRIBUTED.

Correlations LESS than these critical values MAY BE ACCEPTABLE, and
rejection of the hypothesis is not necessarily warranted.

The Kolmogorov-Smirnov test can be used to further evaluate the residuals.
-------------------------------------------------------------------------


*******************************************************************************

               END OF PHASE 22,

          CHECK THAT EXECUTION WAS SUCCESSFUL,

          IF SO NOTE:

          THESE STATISTICS ARE PRINTED FOR THE INITIAL PARAMETER VALUES.
          AFTER REVIEWING THESE VALUES, CONSIDER POSSIBLE RE-PARAMETERIZATION.
```

```
****************************************************************
            UCODE VERSION 3.02 (OCTOBER 2000)
            Documented in: USGS WRI98-4080
         by Eileen P. Poeter and Mary C. Hill
   UPDATES can be obtained from http://water.usgs.gov/
         OR from http://www.mines.edu/igwmc/freeware/ucode
****************************************************************


ECHO OF INPUT

DOS or MS-Windows PLATFORM

PHASE SELECTED ..................................................... 3

REGRESSION CONTROLS:

     SENSITIVITY DIFFERENCING (1=FORWARD, 2= CENTRAL) .............. 2
     PARAMETER ESTIMATION CONVERGES WHEN EITHER OF THE
                                FOLLOWING IS SATISFIED:
       1) MAXIMUM FRACTIONAL PARAMETER CHANGE IS LESS THAN .......... 0.010000
       2) SUM-OF-SQUARED WEIGHTED RESIDUALS DIFFERS OVER
              THREE ITERATIONS BY LESS THAN A FACTOR OF: ............ 0.000100
     IF THE PARAMETER CHANGE VECTOR DIVERGES BY GREATER THAN ........ 85
                    DEGREES FROM THE DOWN GRADIENT DIRECTION
                        THE MARQUARDT PARAMETER WILL BE USED
     THE MARQUARDT FACTOR WILL BE ................................... 1.5
     THE MARQUARDT INCREMENT WILL BE ................................ 0.001
     OPTIONAL QUASI-NEWTON UPDATING (0= NO 1=YES) ................... 0
     MAXIMUM NUMBER OF PARAMETER ITERATIONS BEFORE TERMINATION ...... 10
     MAXIMUM ALLOWABLE FRACTIONAL PARAMETER CHANGE ................. 2.0

     NAME OF INVERSION ALGORITHM IS         mrdrive

     NUMBER OF APPLICATION CODES TO RUN IS .......................... 1
          CODE NAME                        G-UCODE.bat


PRINTING CONTROLS:

     SENSITIVITY SCALING (0=NO-SCALING 1=DIMENSIONLESS 2=1% 3= 1&2) . 1
     INTERMEDIATE PRINTING (0=NONE, 1= PRINT) ....................... 1
     PRODUCE GRAPHING AND POSTPROCESSING FILES (0=NO, 1=YES) ........ 1
     # OF RESIDUAL SETS FOR EVALUATION OF APPARENT NON-RANDOMNESS ... 0


OBSERVATION INFORMATION:

 NUMBER OF OBSERVATIONS = 15

 OBS#    OBSERVATION ID        VALUE           STAT    STAT     SQRT       PLOT
                                                       TYPE    WEIGHT     SYMBOL

    1                A        207.75              2    STD          0.5        1
    2                B        206.86              2    STD          0.5        1
    3                C        206.88              2    STD          0.5        1
    4                D        208.56              2    STD          0.5        1
    5                E        207.66              2    STD          0.5        1
    6                F        206.61              2    STD          0.5        1
    7         5503800f         10500            0.2     CV    0.0004762        2
    8         5506350f         39800            0.2     CV    0.0001256        2
```

9	5506800f	29300	0.2	CV	0.0001706	2
10	5502500f	85300	0.2	CV	5.862e-005	2
11	5507600f	13300	0.2	CV	0.0003759	2
12	MTL1	184.92	1	STD	1	3
13	MTL2	184.92	1	STD	1	3
14	MTL3	184.91	1	STD	1	3
15	05507700	184.9	1	STD	1	3

PARAMETER INFORMATION:

INITIAL INFORMATION FOR 3 PARAMETERS

PARAMETER NAME	INITIAL VALUE	REASONABLE MINIMUM	REASONABLE MAXIMUM	PERTURBATION FRACTIONAL AMOUNT	LOG TRANS FLAG	ESTIMATE FLAG
AreaK_____	5	0.5	50	0.01	YES	YES
Am1_______	100	10	1000	0.01	YES	YES
AreaRech__	0.000195	1.95e-005	0.00195	0.01	NO	YES

FUNCTION INFORMATION:

Functions are used for parameter AreaRech____ in file Billrev7.tpl

Parameter <AreaRech____> is MANIPULATED by a function 1 times in file Billrev7.tpl

TEMPLATE PARAMETER INFORMATION:

```
Analyzing Parameter IDs in file: {Billrev7.tpl}
  {3} lines out of {1904} include Parameter IDs for substitution
     the last line with a substitution is {30}
  Parameter ID: {!AreaK_______!} occurs: {1} times in the template file
  Parameter ID: {!AreaRech____!} occurs: {1} times in the template file
  Parameter ID: {!Am1_________!} occurs: {1} times in the template file
```

****

EXECUTING MRDRIVE VERSION 1.08 (NOV 1998)

****

OBSERVATIONS

OBS#	OBSERVATION NAME	MEASURED VALUE	SIMULATED VALUE	RESIDUAL	WEIGHT**.5	WEIGHTED RESIDUAL

```
    1 A                207.750      208.150    -0.4002    0.500     -0.2001
    2 B                206.860      208.177     -1.317    0.500     -0.6583
    3 C                206.880      208.182     -1.302    0.500     -0.6509
    4 D                208.560      208.104     0.4561    0.500      0.2281
    5 E                207.660      208.041    -0.3808    0.500     -0.1904
    6 F                206.610      208.002     -1.392    0.500     -0.6962
    7 5503800f         10500.0      11826.7     -1327.    4.762E-04-0.6318
    8 5506350f         39800.0      37308.4      2492.    1.256E-04 0.3130
    9 5506800f         29300.0      28581.2      718.8    1.706E-04 0.1227
   10 5502500f         85300.0      83054.6      2245.    5.862E-05 0.1316
   11 5507600f         13300.0      12602.7      697.3    3.759E-04 0.2621
   12 MTL1             184.920      183.197      1.723     1.00        1.723
   13 MTL2             184.920      183.197      1.723     1.00        1.723
   14 MTL3             184.910      183.197      1.713     1.00        1.713
   15 05507700         184.900      183.197      1.703     1.00        1.703

 STATISTICS FOR THESE RESIDUALS :
 MAXIMUM WEIGHTED RESIDUAL  : 0.172E+01 OBS#     12 MTL1
 MINIMUM WEIGHTED RESIDUAL  :-0.696E+00 OBS#      6 F
 AVERAGE WEIGHTED RESIDUAL  : 0.326E+00
 # RESIDUALS >= 0. :       9
 # RESIDUALS < 0.  :       6
 NUMBER OF RUNS  :     4  IN   15 OBSERVATIONS

 SUM OF SQUARED WEIGHTED RESIDUALS           13.835

 SUM OF SQUARED WEIGHTED RESIDUALS (WITH PRIOR)  13.835

 STATISTICS FOR ALL RESIDUALS :
 AVERAGE WEIGHTED RESIDUAL  : 0.326E+00
 # RESIDUALS >= 0. :       9
 # RESIDUALS < 0.  :       6
 NUMBER OF RUNS  :     4  IN   15 OBSERVATIONS

 INTERPRETTING THE CALCULATED RUNS STATISTIC VALUE OF     -2.07
 NOTE: THE FOLLOWING APPLIES ONLY IF
        # RESIDUALS >= 0. IS > 10 AND
        # RESIDUALS <  0. IS > 10
 THE NEGATIVE VALUE MAY INDICATE TOO FEW RUNS:
    IF THE VALUE IS < -1.28 , THERE IS < 10% CHANCE THE VALUES ARE RANDOM,
    IF THE VALUE IS < -1.645, THERE IS < 5% CHANCE THE VALUES ARE RANDOM,
    IF THE VALUE IS < -1.96 , THERE IS < 2.5% CHANCE THE VALUES ARE RANDOM



*********************************************************************************


 DIMENSIONLESS SCALED SENSITIVITIES (SCALED BY (PARAMETER_VALUE*(wt**.5))

 PARAMETER #:          1          2          3
 PARAMETER ID:     AreaK_____Am1_______AreaRech__
 OBS# OBS ID
    1 A            -6.75E-01 -6.04E-01  1.21E+00
    2 B            -6.75E-01 -6.08E-01  1.21E+00
    3 C            -6.75E-01 -6.08E-01  1.21E+00
    4 D            -6.86E-01 -6.04E-01  1.22E+00
    5 E            -6.80E-01 -5.76E-01  1.21E+00
    6 F            -6.77E-01 -5.57E-01  1.20E+00
    7 5503800f     -9.65E+00 -1.96E+01  1.59E+01
```

```
   8 5506350f       1.90E+00 -3.07E-01  3.67E+00
   9 5506800f       1.72E+00 -7.52E-03  2.32E+00
  10 5502500f       1.48E+00 -5.49E-01  2.57E+00
  11 5507600f      -2.40E+00  9.87E-02  5.71E+00
  12 MTL1           4.79E-02  0.00E+00  2.40E-01
  13 MTL2           4.79E-02  0.00E+00  2.40E-01
  14 MTL3           4.79E-02  0.00E+00  2.40E-01
  15 05507700       4.79E-02  0.00E+00  2.40E-01

 COMPOSITE SCALED SENSITIVITIES
 ((SUM OF THE SQUARED VALUES)/ND)**.5

 PARAMETER #:          1         2         3
 PARAMETER ID:     AreaK_____Am1_______AreaRech__
                     2.71      5.09      4.61

 SCALED LEAST-SQUARES MATRIX :
   1.0000      0.91908     -0.83638
  0.91908       1.0000     -0.90355
 -0.83638     -0.90355       1.0000

 SCALED GRADIENT VECTOR :
  0.78588      0.68722     -0.43258


**************************************************


 ITERATION NO. =      1
 VALUES FROM LEAST-SQUARES REGRESSION PROCEDURE :
   MARQUARDT PARAMETER -------------- = 0.00000
   MAX. FRACTIONAL PAR. CHANGE------- = 0.17619
   MAX. FRAC. CHANGE OCCURRED FOR PAR.#      2, Am1_______

   UPDATED ESTIMATES OF REGRESSION PARAMETERS :
 AreaK_____   Am1_______   AreaRech__
   5.8576      117.62      2.06580E-04


**************************************************



 OBSERVATIONS

       OBSERVATION    MEASURED  SIMULATED                             WEIGHTED
 OBS#      NAME       VALUE       VALUE        RESIDUAL  WEIGHT**.5   RESIDUAL

     1 A              207.750     208.065     -0.3146    0.500     -0.1573
     2 B              206.860     208.091      -1.231    0.500     -0.6154
     3 C              206.880     208.096      -1.216    0.500     -0.6080
     4 D              208.560     208.018      0.5423    0.500      0.2712
     5 E              207.660     207.957     -0.2967    0.500     -0.1484
     6 F              206.610     207.920      -1.310    0.500     -0.6548
     7 5503800f       10500.0     10253.2       246.8    4.762E-04 0.1175
     8 5506350f       39800.0     40640.0      -840.0    1.256E-04-0.1055
     9 5506800f       29300.0     30380.2      -1080.    1.706E-04-0.1843
    10 5502500f       85300.0     87905.4      -2605.    5.862E-05-0.1527
```

```
   11 5507600f        13300.0       12875.8       424.2     3.759E-04 0.1595
   12 MTL1            184.920       183.217       1.702      1.00       1.702
   13 MTL2            184.920       183.217       1.702      1.00       1.702
   14 MTL3            184.910       183.217       1.693      1.00       1.693
   15 05507700        184.900       183.217       1.682      1.00       1.682

STATISTICS FOR THESE RESIDUALS :
MAXIMUM WEIGHTED RESIDUAL  : 0.170E+01 OBS#     12 MTL1
MINIMUM WEIGHTED RESIDUAL  :-0.655E+00 OBS#      6 F
AVERAGE WEIGHTED RESIDUAL  : 0.313E+00
# RESIDUALS >= 0. :       7
# RESIDUALS < 0.  :       8
NUMBER OF RUNS  :    6  IN   15 OBSERVATIONS

SUM OF SQUARED WEIGHTED RESIDUALS          12.897

SUM OF SQUARED WEIGHTED RESIDUALS (WITH PRIOR)  12.897

STATISTICS FOR ALL RESIDUALS :
AVERAGE WEIGHTED RESIDUAL  : 0.313E+00
# RESIDUALS >= 0. :       7
# RESIDUALS < 0.  :       8
NUMBER OF RUNS  :    6  IN   15 OBSERVATIONS

INTERPRETTING THE CALCULATED RUNS STATISTIC VALUE OF     -1.06
NOTE: THE FOLLOWING APPLIES ONLY IF
       # RESIDUALS >= 0. IS > 10 AND
       # RESIDUALS <  0. IS > 10
THE NEGATIVE VALUE MAY INDICATE TOO FEW RUNS:
   IF THE VALUE IS < -1.28 , THERE IS < 10% CHANCE THE VALUES ARE RANDOM,
   IF THE VALUE IS < -1.645, THERE IS < 5% CHANCE THE VALUES ARE RANDOM,
   IF THE VALUE IS < -1.96 , THERE IS < 2.5% CHANCE THE VALUES ARE RANDOM



*******************************************************************************


DIMENSIONLESS SCALED SENSITIVITIES (SCALED BY (PARAMETER_VALUE*(wt**.5))

PARAMETER #:          1          2          3
PARAMETER ID:     AreaK_____Am1_______AreaRech__
OBS# OBS ID
   1 A            -1.38E+00 -1.96E+00  1.84E+00
   2 B            -1.38E+00 -1.97E+00  1.84E+00
   3 C            -1.38E+00 -1.97E+00  1.84E+00
   4 D            -1.39E+00 -1.94E+00  1.84E+00
   5 E            -1.38E+00 -1.91E+00  1.83E+00
   6 F            -1.37E+00 -1.89E+00  1.82E+00
   7 5503800f     -9.24E+00 -1.62E+01  1.29E+01
   8 5506350f      2.52E+00 -4.11E-01  3.83E+00
   9 5506800f      2.00E+00 -2.48E-02  2.44E+00
  10 5502500f      1.54E+00 -1.03E+00  3.03E+00
  11 5507600f     -2.62E+00  1.60E-01  5.76E+00
  12 MTL1          7.96E-02 -2.55E-02  2.45E-01
  13 MTL2          7.96E-02 -2.55E-02  2.45E-01
  14 MTL3          7.96E-02 -2.55E-02  2.45E-01
  15 05507700      7.96E-02 -2.55E-02  2.45E-01

COMPOSITE SCALED SENSITIVITIES
```

```
((SUM OF THE SQUARED VALUES)/ND)**.5

PARAMETER #:          1          2          3
PARAMETER ID:      AreaK_____Am1_______AreaRech__
                     2.79       4.37       4.08

SCALED LEAST-SQUARES MATRIX :
  1.0000      0.89082     -0.76318
 0.89082       1.0000     -0.87550
-0.76318     -0.87550       1.0000

SCALED GRADIENT VECTOR :
 7.38976E-02  0.10967     -4.64002E-02


**************************************************


ITERATION NO. =      2
VALUES FROM LEAST-SQUARES REGRESSION PROCEDURE :
  MARQUARDT PARAMETER -------------- = 0.00000
  MAX. FRACTIONAL PAR. CHANGE------- = 0.12643
  MAX. FRAC. CHANGE OCCURRED FOR PAR.#      2, Am1_______

  UPDATED ESTIMATES OF REGRESSION PARAMETERS :
AreaK_____    Am1_______    AreaRech__
  5.7311        132.49       2.09484E-04


**************************************************



OBSERVATIONS

      OBSERVATION    MEASURED  SIMULATED                         WEIGHTED
OBS#      NAME       VALUE       VALUE        RESIDUAL  WEIGHT**.5   RESIDUAL

    1 A              207.750     208.050     -0.2998    0.500     -0.1499
    2 B              206.860     208.076      -1.216    0.500     -0.6079
    3 C              206.880     208.081      -1.201    0.500     -0.6005
    4 D              208.560     208.004      0.5559    0.500      0.2779
    5 E              207.660     207.944     -0.2844    0.500     -0.1422
    6 F              206.610     207.908      -1.298    0.500     -0.6490
    7 5503800f       10500.0     9938.35       561.7    4.762E-04 0.2675
    8 5506350f       39800.0     40614.3      -814.3    1.256E-04-0.1023
    9 5506800f       29300.0     30456.8      -1157.    1.706E-04-0.1974
   10 5502500f       85300.0     87885.8      -2586.    5.862E-05-0.1516
   11 5507600f       13300.0     13171.2       128.8    3.759E-04 4.8432E-02
   12 MTL1           184.920     183.220       1.700     1.00       1.700
   13 MTL2           184.920     183.220       1.700     1.00       1.700
   14 MTL3           184.910     183.220       1.690     1.00       1.690
   15 05507700       184.900     183.220       1.680     1.00       1.680

STATISTICS FOR THESE RESIDUALS :
MAXIMUM WEIGHTED RESIDUAL  : 0.170E+01 OBS#      12 MTL1
MINIMUM WEIGHTED RESIDUAL  :-0.649E+00 OBS#       6 F
AVERAGE WEIGHTED RESIDUAL  : 0.317E+00
```

```
# RESIDUALS >= 0. :       7
# RESIDUALS < 0.  :       8
NUMBER OF RUNS  :    6  IN   15 OBSERVATIONS

SUM OF SQUARED WEIGHTED RESIDUALS           12.872

SUM OF SQUARED WEIGHTED RESIDUALS (WITH PRIOR)  12.872

STATISTICS FOR ALL RESIDUALS :
AVERAGE WEIGHTED RESIDUAL  : 0.317E+00
# RESIDUALS >= 0. :       7
# RESIDUALS < 0.  :       8
NUMBER OF RUNS  :    6  IN   15 OBSERVATIONS

INTERPRETTING THE CALCULATED RUNS STATISTIC VALUE OF     -1.06
NOTE: THE FOLLOWING APPLIES ONLY IF
       # RESIDUALS >= 0. IS > 10 AND
       # RESIDUALS <  0. IS > 10
THE NEGATIVE VALUE MAY INDICATE TOO FEW RUNS:
   IF THE VALUE IS < -1.28 , THERE IS < 10% CHANCE THE VALUES ARE RANDOM,
   IF THE VALUE IS < -1.645, THERE IS < 5% CHANCE THE VALUES ARE RANDOM,
   IF THE VALUE IS < -1.96 , THERE IS < 2.5% CHANCE THE VALUES ARE RANDOM



********************************************************************************


DIMENSIONLESS SCALED SENSITIVITIES (SCALED BY (PARAMETER_VALUE*(wt**.5))

PARAMETER #:          1         2         3
PARAMETER ID:     AreaK_____Am1_______AreaRech__
OBS# OBS ID
   1 A            -1.26E+00 -2.13E+00  1.83E+00
   2 B            -1.26E+00 -2.13E+00  1.83E+00
   3 C            -1.26E+00 -2.13E+00  1.83E+00
   4 D            -1.26E+00 -2.10E+00  1.83E+00
   5 E            -1.26E+00 -2.07E+00  1.82E+00
   6 F            -1.25E+00 -2.05E+00  1.81E+00
   7 5503800f     -8.80E+00 -2.00E+01  1.32E+01
   8 5506350f      2.28E+00 -2.13E+00  4.10E+00
   9 5506800f      2.21E+00 -5.67E-02  2.33E+00
  10 5502500f      1.70E+00 -1.14E+00  2.87E+00
  11 5507600f     -2.74E+00 -5.89E-01  5.98E+00
  12 MTL1          7.06E-02  0.00E+00  2.55E-01
  13 MTL2          7.06E-02  0.00E+00  2.55E-01
  14 MTL3          7.06E-02  0.00E+00  2.55E-01
  15 05507700      7.06E-02  0.00E+00  2.55E-01

COMPOSITE SCALED SENSITIVITIES
((SUM OF THE SQUARED VALUES)/ND)**.5

PARAMETER #:          1         2         3
PARAMETER ID:     AreaK_____Am1_______AreaRech__
                    2.68      5.37      4.17

SCALED LEAST-SQUARES MATRIX :
  1.0000      0.86550     -0.75835
 0.86550       1.0000     -0.90115
-0.75835     -0.90115       1.0000
```

```
 SCALED GRADIENT VECTOR :
 -5.65236E-02 -4.98895E-02  5.07751E-02

**************************************************

 ITERATION NO. =      3
 VALUES FROM LEAST-SQUARES REGRESSION PROCEDURE :
   MARQUARDT PARAMETER -------------- = 0.00000
   MAX. FRACTIONAL PAR. CHANGE------- = -.94546E-02
   MAX. FRAC. CHANGE OCCURRED FOR PAR.#      1, AreaK_____

   UPDATED ESTIMATES OF REGRESSION PARAMETERS :
 AreaK_____    Am1_______    AreaRech__
   5.6769        133.51       2.09970E-04

**************************************************

SUM OF SQUARED RESIDUALS FOR PARAMETERS AS UPDATED IN ITERATION NO.  3
  SUM OF SQUARED WEIGHTED RESIDUALS               1.28701e+001
  SUM OF SQUARED WEIGHTED RESIDUALS (WITH PRIOR) 1.28701e+001

******************************************************************************
*                                                                            *
* NOTE THAT THE FINAL ITERATION RESULTED IN PARAMETERS THAT PRODUCED A LOWER *
* SUM-OF-SQUARED RESIDUALS THAN ANY EARLIER ITERATION                        *
*                                                                            *
******************************************************************************

 PARAMETER ESTIMATION CONVERGED BY SATISFYING PARAMETER TOLERANCE CRITERIA

 ****************************************************************************
                  PARAMETER ESTIMATION CONVERGED
               THE FOLLOWING RESIDUALS AND STATISTICS
 ARE CALCULATED AT THE FINAL PARAMETER VALUES USING CENTRAL DIFFERENCES
 ****************************************************************************


 OBSERVATIONS

       OBSERVATION     MEASURED  SIMULATED                              WEIGHTED
 OBS#     NAME         VALUE       VALUE        RESIDUAL  WEIGHT**.5    RESIDUAL

     1 A              207.750      208.066     -0.3157    0.500     -0.1578
     2 B              206.860      208.092      -1.232    0.500     -0.6159
     3 C              206.880      208.097      -1.217    0.500     -0.6084
     4 D              208.560      208.020      0.5399    0.500      0.2699
     5 E              207.660      207.960     -0.3004    0.500     -0.1502
     6 F              206.610      207.924      -1.314    0.500     -0.6570
     7 5503800f       10500.0      10036.0       464.0    4.762E-04 0.2209
     8 5506350f       39800.0      40562.4      -762.4    1.256E-04-9.5775E-02
```

```
   9 5506800f        29300.0       30428.6      -1129.    1.706E-04-0.1926
  10 5502500f        85300.0       87807.3      -2507.    5.862E-05-0.1470
  11 5507600f        13300.0       13244.1       55.93    3.759E-04 2.1026E-02
  12 MTL1            184.920       183.221       1.699     1.00       1.699
  13 MTL2            184.920       183.221       1.699     1.00       1.699
  14 MTL3            184.910       183.221       1.689     1.00       1.689
  15 05507700        184.900       183.221       1.679     1.00       1.679

STATISTICS FOR THESE RESIDUALS :
MAXIMUM WEIGHTED RESIDUAL  : 0.170E+01 OBS#     12 MTL1
MINIMUM WEIGHTED RESIDUAL  :-0.657E+00 OBS#      6 F
AVERAGE WEIGHTED RESIDUAL  : 0.310E+00
# RESIDUALS >= 0. :       7
# RESIDUALS < 0.  :       8
NUMBER OF RUNS  :    6  IN   15 OBSERVATIONS

SUM OF SQUARED WEIGHTED RESIDUALS           12.870

SUM OF SQUARED WEIGHTED RESIDUALS (WITH PRIOR)  12.870

STATISTICS FOR ALL RESIDUALS :
AVERAGE WEIGHTED RESIDUAL  : 0.310E+00
# RESIDUALS >= 0. :       7
# RESIDUALS < 0.  :       8
NUMBER OF RUNS  :    6  IN   15 OBSERVATIONS

INTERPRETTING THE CALCULATED RUNS STATISTIC VALUE OF     -1.06
NOTE: THE FOLLOWING APPLIES ONLY IF
       # RESIDUALS >= 0. IS > 10 AND
       # RESIDUALS <  0. IS > 10
THE NEGATIVE VALUE MAY INDICATE TOO FEW RUNS:
   IF THE VALUE IS < -1.28 , THERE IS < 10% CHANCE THE VALUES ARE RANDOM,
   IF THE VALUE IS < -1.645, THERE IS < 5% CHANCE THE VALUES ARE RANDOM,
   IF THE VALUE IS < -1.96 , THERE IS < 2.5% CHANCE THE VALUES ARE RANDOM




DIMENSIONLESS SCALED SENSITIVITIES (SCALED BY (PARAMETER_VALUE*(wt**.5))

PARAMETER #:          1          2          3
PARAMETER ID:       AreaK_____Aml_______AreaRech__
OBS# OBS ID
   1 A              -1.25E+00 -2.41E+00  1.85E+00
   2 B              -1.25E+00 -2.42E+00  1.85E+00
   3 C              -1.25E+00 -2.42E+00  1.85E+00
   4 D              -1.25E+00 -2.39E+00  1.85E+00
   5 E              -1.25E+00 -2.35E+00  1.84E+00
   6 F              -1.24E+00 -2.33E+00  1.83E+00
   7 5503800f       -8.71E+00 -1.98E+01  1.33E+01
   8 5506350f        2.22E+00 -6.03E-01  4.11E+00
   9 5506800f        1.94E+00  6.77E-01  2.47E+00
  10 5502500f        1.71E+00 -9.00E-01  2.89E+00
  11 5507600f       -2.72E+00  5.52E-02  6.00E+00
  12 MTL1            6.09E-02  2.24E-02  2.55E-01
  13 MTL2            6.09E-02  2.24E-02  2.55E-01
  14 MTL3            6.09E-02  2.24E-02  2.55E-01
  15 05507700        6.09E-02  2.24E-02  2.55E-01
```

```
COMPOSITE SCALED SENSITIVITIES
((SUM OF THE SQUARED VALUES)/ND)**.5

PARAMETER #:          1         2         3
PARAMETER ID:      AreaK_____Am1_______AreaRech__
                    2.64      5.34      4.19

         ----------------
         COVARIANCE MAT.
         ----------------

           1           2           3
...................................................
  1    0.1538     -0.2005     -5.8583E-07
  2   -0.2005      0.5072      1.2428E-05
  3   -5.8583E-07  1.2428E-05  7.3488E-10


_________________

PARAMETER SUMMARY
_________________

________________________________________________________________________

PARAMETER VALUES IN "REGRESSION" SPACE --- LOG TRANSFORMED AS APPLICABLE
________________________________________________________________________

PARAMETER #:          1          2          3
PARAMETER ID:      AreaK_____ Am1_______ AreaRech__
* = LOG TRNS:         *          *


UPPER 95% C.I.      1.13E+00   2.80E+00   2.69E-04
FINAL VALUES        7.54E-01   2.13E+00   2.10E-04
LOWER 95% C.I.      3.83E-01   1.45E+00   1.51E-04

STD. DEV.           1.70E-01   3.09E-01   2.71E-05

COEF. OF VAR.
* if value=0        2.26E-01   1.46E-01   1.29E-01

------------------------------------------------------------------------
------------------------------------------------------------------------

________________________________________________________________________

PHYSICAL PARAMETER VALUES --- EXP10 OF LOG TRANSFORMED PARAMETERS
________________________________________________________________________

PARAMETER #:          1          2          3
PARAMETER ID:      AreaK_____ Am1_______ AreaRech__
* = LOG TRNS:      *          *

UPPER 95% C.I.      1.33E+01   6.30E+02   2.69E-04
FINAL VALUES        5.68E+00   1.34E+02   2.10E-04
LOWER 95% C.I.      2.42E+00   2.83E+01   1.51E-04

    REASONABLE
   UPPER LIMIT      5.00E+01   1.00E+03   1.95E-03
    REASONABLE
```

```
   LOWER LIMIT     5.00E-01   1.00E+01   1.95E-05

ESTIMATE ABOVE (1)
 BELOW(-1)LIMITS       0          0          0
ENTIRE CONF. INT.
 ABOVE(1)BELOW(-1)     0          0          0


          ----------------
          CORRELATION MAT.
          ----------------

            1           2           3
 .........................................
   1     1.000      -0.7179     -5.5099E-02
   2   -0.7179       1.000       0.6437
   3   -5.5099E-02  0.6437       1.000

 THE CORRELATION OF THE FOLLOWING PARAMETER PAIRS >= .95
     PARAMETER  #    ID           #   ID           CORRELATION

 THE CORRELATION OF THE FOLLOWING PARAMETER PAIRS IS BETWEEN .90 AND .95
     PARAMETER  #    ID           #   ID           CORRELATION

 THE CORRELATION OF THE FOLLOWING PARAMETER PAIRS IS BETWEEN .85 AND .90
     PARAMETER  #    ID           #   ID           CORRELATION


  LEAST-SQUARES OBJ FUNC (DEP.VAR. ONLY)- =  12.870
  LEAST-SQUARES OBJ FUNC (W/PARAMETERS)-- =  12.870
  CALCULATED ERROR VARIANCE-------------- =  1.0725
  STANDARD ERROR OF THE REGRESSION------- =  1.0356
  CORRELATION COEFFICIENT---------------- = 0.99996
       W/PARAMETERS---------------------- = 0.99996
  ITERATIONS----------------------------- =       3

       MAX LIKE OBJ FUNC =  134.63
       AIC STATISTIC---- =  140.63
       BIC STATISTIC---- =  142.76

 ORDERED DEPENDENT-VARIABLE WEIGHTED RESIDUALS
 NUMBER OF RESIDUALS INCLUDED:         15
  -0.657       -0.616       -0.608       -0.193       -0.158       -0.150
  -0.147       -0.958E-01   0.210E-01    0.221        0.270         1.68
    1.69         1.70         1.70
 CORRELATION BETWEEN ORDERED WEIGHTED RESIDUALS
                                  AND NORMAL ORDER STATISTICS =      0.804
     (CALCULATED USING EQ.38 OF HILL,1992 OR EQ.23 OF HILL,1998)

 ----------------------------------------------------------------------
 COMMENTS ON THE INTERPRETATION OF THE CORRELATION BETWEEN
 WEIGHTED RESIDUALS AND NORMAL ORDER STATISTICS:

 Generally, IF the reported CORRELATION is LESS than the critical value,
 at the selected significance level (usually 5 or 10%), the hypothesis
 that the weighted residuals are INDEPENDENT AND NORMALLY DISTRIBUTED
 would be REJECTED.  HOWEVER, in this case, conditions are outside of
 the range of published critical values as discussed below.

 The sum of the number of observations and prior information items is    15
 which is less than 35, the minimum value for which critical values are
```

published. Therefore, the critical values for the 5 and 10% significance levels are less than 0.943 and 0.952, respectively.

CORRELATIONS GREATER than these critical values indicate that, probably, the weighted residuals ARE INDEPENDENT AND NORMALLY DISTRIBUTED.

Correlations LESS than these critical values MAY BE ACCEPTABLE, and rejection of the hypothesis is not necessarily warranted.

The Kolmogorov-Smirnov test can be used to further evaluate the residuals.

```
-------------------------------------------------------------------------

>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

  PARAMETER VALUES AND STATISTICS FOR ALL ITERATIONS


PARAMETER NAMES
 AreaK_____ Am1_______ AreaRech__

INITIAL PARAMETER VALUES
   5.00        100.        0.195E-03
                                          LEAST  SQUARES
                                          OBJ    OBJ FNC
                                          FUNC   W/PRIOR  MAX-CHG  PARAM    MARQRDT
                                        14.      14.      0.18     Am1_______ 0.00
iteration #  1
   5.86        118.        0.207E-03
                                        13.      13.      0.13     Am1_______ 0.00
iteration #  2
   5.73        132.        0.209E-03
                                        13.      13.      -.95E-02 AreaK_____ 0.00
iteration #  3
   5.68        134.        0.210E-03
                                           13       13


*****************************************************************************
              PARAMETER ESTIMATION CONVERGED
*****************************************************************************
```

APPENDIX E

PEST Input File

```
pcf
* control data
restart estimation
12 15 3 0 3
1  1  double  point  1  0  0
1.000000e+001  2.000000e+000  3.000000e-001  1.000000e-002  10
1.000000e+001  1.000000e+001  1.000000e-003
1.000000e-001 noaui
20  1.000000e-002  3  3  1.000000e-002  3
1  1  1
* parameter groups
Kh      relative   1.000000e-002  0.000000e+000  switch  2.000000e+000  parabolic
Khi     relative   1.000000e-002  0.000000e+000  switch  2.000000e+000  parabolic
Rch     relative   1.000000e-002  0.000000e+000  switch  2.000000e+000  parabolic
* parameter data
AreaK_______ log   factor   5      .5     50    Kh      1.0      0.0 1
Am1_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am10________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am2_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am3_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am4_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am5_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am6_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am7_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am8_________ log   factor   100    10     1000  Khi     1.0      0.0 1
Am9_________ log   factor   100    10     1000  Khi     1.0      0.0 1
AreaRech____ none  factor   .000195       .0000195      .00195       Rch    -1.0
0.0 1
* observation groups
Head
Streamflow
Lakestage
* observation data
A 207.75     1.000000 Head
B 206.86     1.000000 Head
C 206.88     1.000000 Head
D 208.56     1.000000 Head
E 207.66     1.000000 Head
F 206.61     1.000000 Head
5503800f 10500      10.000000 Streamflow
5506350f 39800      10.000000 Streamflow
5506800f 29300      10.000000 Streamflow
5502500f 85300      10.000000 Streamflow
5507600f 13300      10.000000 Streamflow
MTL1 184.92  1.000000 Lakestage
MTL2 184.92  1.000000 Lakestage
MTL3 184.91  1.000000 Lakestage
05507700 184.9      1.000000 Lakestage
* model command line
G-PEST.bat
* model input/output
best.tpl best.DAT
best.ins best.XTR
```

APPENDIX F

PEST Output File

PEST RUN RECORD: CASE best

PEST run mode:-

Parameter estimation mode

Case dimensions:-

Number of parameters	:	12
Number of adjustable parameters	:	12
Number of parameter groups	:	3
Number of observations	:	15
Number of prior estimates	:	0

Model command line(s):-

G-PEST.bat

Jacobian command line:-

na

Model interface files:-

Templates:
best.tpl
for model input files:
best.DAT

(Parameter values written using double precision protocol.)
(Decimal point always included.)

Instruction files:
best.ins
for reading model output files:
best.XTR

PEST-to-model message file:-

na

Derivatives calculation:-

Param group	Increment type	Increment	Increment low bound	Forward or central	Multiplier (central)	Method (central)
kh	relative	1.0000E-02	none	switch	2.000	parabolic
khi	relative	1.0000E-02	none	switch	2.000	parabolic
rch	relative	1.0000E-02	none	switch	2.000	parabolic

Parameter definitions:-

Name	Trans-formation	Change limit	Initial value	Lower bound	Upper bound
areak	log	factor	5.00000	0.500000	50.0000
am1	log	factor	100.000	10.0000	1000.00
am10	log	factor	100.000	10.0000	1000.00
am2	log	factor	100.000	10.0000	1000.00
am3	log	factor	100.000	10.0000	1000.00
am4	log	factor	100.000	10.0000	1000.00
am5	log	factor	100.000	10.0000	1000.00

am6________	log	factor	100.000	10.0000	1000.00
am7________	log	factor	100.000	10.0000	1000.00
am8________	log	factor	100.000	10.0000	1000.00
am9________	log	factor	100.000	10.0000	1000.00
arearech____	none	factor	1.950000E-04	1.950000E-05	1.950000E-03

Name	Group	Scale	Offset	Model command number
areak_______	kh	1.00000	0.00000	1
am1_________	khi	1.00000	0.00000	1
am10________	khi	1.00000	0.00000	1
am2_________	khi	1.00000	0.00000	1
am3_________	khi	1.00000	0.00000	1
am4_________	khi	1.00000	0.00000	1
am5_________	khi	1.00000	0.00000	1
am6_________	khi	1.00000	0.00000	1
am7_________	khi	1.00000	0.00000	1
am8_________	khi	1.00000	0.00000	1
am9_________	khi	1.00000	0.00000	1
arearech____	rch	-1.00000	0.00000	1

Prior information:-

No prior information supplied

Observations:-

Observation name	Observation	Weight	Group
a	207.750	1.000	head
b	206.860	1.000	head
c	206.880	1.000	head
d	208.560	1.000	head
e	207.660	1.000	head
f	206.610	1.000	head
5503800f	10500.0	10.00	streamflow
5506350f	39800.0	10.00	streamflow
5506800f	29300.0	10.00	streamflow
5502500f	85300.0	10.00	streamflow
5507600f	13300.0	10.00	streamflow
mtl1	184.920	1.000	lakestage
mtl2	184.920	1.000	lakestage
mtl3	184.910	1.000	lakestage
05507700	184.900	1.000	lakestage

Control settings:-

```
   Initial lambda                                              :  10.000
   Lambda adjustment factor                                    :  2.0000
   Sufficient new/old phi ratio per optimisation iteration     : 0.30000
   Limiting relative phi reduction between lambdas             : 1.00000E-02
   Maximum trial lambdas per iteration                         :  10

   Maximum  factor  parameter change (factor-limited changes)  :  10.000
   Maximum relative parameter change (relative-limited changes) :   na
   Fraction of initial parameter values used in computing
   change limit for near-zero parameters                       : 1.00000E-03
   Allow bending of parameter upgrade vector                   : no
   Allow parameters to stick to their bounds                   : no

   Relative phi reduction below which to begin use of
   central derivatives                                         : 0.10000

   Relative phi reduction indicating convergence               : 0.10000E-01
   Number of phi values required within this range             :    3
   Maximum number of consecutive failures to lower phi         :    3
   Minimal relative parameter change indicating convergence    : 0.10000E-01
   Number of consecutive iterations with minimal param change  :    3
```

```
  Maximum number of optimisation iterations                    :  20

  Attempt automatic user intervention                          : no


                           OPTIMISATION RECORD


INITIAL CONDITIONS:
  Sum of squared weighted residuals (ie phi)                  =  1.39116E+09
  Contribution to phi from observation group "head"           =   24.048
  Contribution to phi from observation group "streamflow"     =  1.39116E+09
  Contribution to phi from observation group "lakestage"      =   11.660

      Current parameter values
      areak_______      5.00000
      am1_________      100.000
      am10________      100.000
      am2_________      100.000
      am3_________      100.000
      am4_________      100.000
      am5_________      100.000
      am6_________      100.000
      am7_________      100.000
      am8_________      100.000
      am9_________      100.000
      arearech____    1.950000E-04


OPTIMISATION ITERATION NO.        :    1
   Model calls so far             :    1
   Starting phi for this iteration                            :  1.39116E+09
   Contribution to phi from observation group "head"          :   24.048
   Contribution to phi from observation group "streamflow"    :  1.39116E+09
   Contribution to phi from observation group "lakestage"     :   11.660

       Lambda =    10.000      ----->
          Phi =  8.59114E+07  (  0.062 of starting phi)

   No more lambdas: phi is less than 0.3000 of starting phi
   Lowest phi this iteration:  8.59114E+07

      Current parameter values                 Previous parameter values
      areak_______      5.64316                areak_______      5.00000
      am1_________      104.001                am1_________      100.000
      am10________      100.439                am10________      100.000
      am2_________      97.6655                am2_________      100.000
      am3_________      98.7647                am3_________      100.000
      am4_________      100.013                am4_________      100.000
      am5_________      94.1460                am5_________      100.000
      am6_________      97.2735                am6_________      100.000
      am7_________      97.6512                am7_________      100.000
      am8_________      99.0002                am8_________      100.000
      am9_________      95.0647                am9_________      100.000
      arearech____    1.980219E-04             arearech____    1.950000E-04
   Maximum   factor change:  1.129     ["areak_______"]
   Maximum relative change: 0.1286     ["areak_______"]


OPTIMISATION ITERATION NO.        :    2
   Model calls so far             :   14
   Starting phi for this iteration                            :  8.59114E+07
   Contribution to phi from observation group "head"          :   23.684
   Contribution to phi from observation group "streamflow"    :  8.59114E+07
   Contribution to phi from observation group "lakestage"     :   13.051

       Lambda =    5.0000      ----->
          Phi =  1.08344E+08  (  1.261 times starting phi)
```

```
     Lambda =   2.5000     ----->
        Phi =  9.02785E+07  (  1.051 times starting phi)

     Lambda =   1.2500     ----->
        Phi =  3.76692E+07  (  0.438 of starting phi)

     Lambda =  0.62500     ----->
        Phi =  9.62262E+07  (  1.120 times starting phi)

 No more lambdas: phi rising
 Lowest phi this iteration:  3.76692E+07

    Current parameter values                Previous parameter values
    areak_______        5.64266             areak_______        5.64316
    am1_________        103.582             am1_________        104.001
    am10________        99.9692             am10________        100.439
    am2_________        97.6026             am2_________        97.6655
    am3_________        98.6343             am3_________        98.7647
    am4_________        99.9293             am4_________        100.013
    am5_________        94.0570             am5_________        94.1460
    am6_________        97.2520             am6_________        97.2735
    am7_________        98.4015             am7_________        97.6512
    am8_________        98.7402             am8_________        99.0002
    am9_________        94.8604             am9_________        95.0647
    arearech____      1.978684E-04          arearech____      1.980219E-04
 Maximum   factor change:  1.008      ["am7_________"]
 Maximum relative change: 7.6835E-03 ["am7_________"]


OPTIMISATION ITERATION NO.        :    3
   Model calls so far             :   30
   Starting phi for this iteration                     :  3.76692E+07
   Contribution to phi from observation group "head"       :   23.785
   Contribution to phi from observation group "streamflow" :  3.76691E+07
   Contribution to phi from observation group "lakestage"  :  1.65568E-02

     Lambda =  0.62500     ----->
        Phi =  8.53379E+07  (  2.265 times starting phi)

     Lambda =  0.31250     ----->
        Phi =  8.18081E+07  (  2.172 times starting phi)

     Lambda =  0.15625     ----->
        Phi =  1.15156E+08  (  3.057 times starting phi)

 No more lambdas: phi rising
 Lowest phi this iteration:  8.18081E+07
 Relative phi reduction between optimisation iterations less than 0.1000
 Switch to central derivatives calculation
 (restart from best parameters so far - these achieved at iteration    2)

    Current parameter values
    areak_______        5.64266
    am1_________        103.582
    am10________        99.9692
    am2_________        97.6026
    am3_________        98.6343
    am4_________        99.9293
    am5_________        94.0570
    am6_________        97.2520
    am7_________        98.4015
    am8_________        98.7402
    am9_________        94.8604
    arearech____      1.978684E-04


OPTIMISATION ITERATION NO.        :    4
   Model calls so far             :   45
```

```
   Starting phi for this iteration                          :  3.76692E+07
   Contribution to phi from observation group "head"        :   23.785
   Contribution to phi from observation group "streamflow"  :  3.76691E+07
   Contribution to phi from observation group "lakestage"   :  1.65568E-02

       Lambda =  0.62500      ----->
          Phi =  6.48867E+07  (  1.723 times starting phi)

       Lambda =  0.31250      ----->
          Phi =  1.07146E+08  (  2.844 times starting phi)

       Lambda =   1.2500      ----->
          Phi =  1.09361E+08  (  2.903 times starting phi)

   No more lambdas: phi rising
   Lowest phi this iteration:  6.48867E+07

      Current parameter values                 Previous parameter values
      areak_______       5.57662               areak_______       5.64266
      am1_________       106.739               am1_________       103.582
      am10________       103.509               am10________       99.9692
      am2_________       99.5549               am2_________       97.6026
      am3_________       99.2958               am3_________       98.6343
      am4_________       98.4296               am4_________       99.9293
      am5_________       94.8951               am5_________       94.0570
      am6_________       97.5535               am6_________       97.2520
      am7_________       99.6968               am7_________       98.4015
      am8_________       99.2033               am8_________       98.7402
      am9_________       94.2108               am9_________       94.8604
      arearech____      1.977145E-04           arearech____      1.978684E-04
   Maximum   factor change:  1.035      ["am10________"]
   Maximum relative change: 3.5408E-02 ["am10________"]


OPTIMISATION ITERATION NO.        :    5
   Model calls so far             :   72
   Starting phi for this iteration                          :  6.48867E+07
   Contribution to phi from observation group "head"        :   24.152
   Contribution to phi from observation group "streamflow"  :  6.48867E+07
   Contribution to phi from observation group "lakestage"   :  8.88684E-03

       Lambda =  0.62500      ----->
          Phi =  8.28702E+07  (  1.277 times starting phi)

       Lambda =  0.31250      ----->
          Phi =  8.13328E+07  (  1.253 times starting phi)

       Lambda =  0.15625      ----->
          Phi =  9.43635E+07  (  1.454 times starting phi)

   No more lambdas: phi rising
   Lowest phi this iteration:  8.13328E+07

      Current parameter values                 Previous parameter values
      areak_______       5.58098               areak_______       5.57662
      am1_________       107.444               am1_________       106.739
      am10________       103.607               am10________       103.509
      am2_________       99.1978               am2_________       99.5549
      am3_________       98.8455               am3_________       99.2958
      am4_________       98.5441               am4_________       98.4296
      am5_________       94.8444               am5_________       94.8951
      am6_________       96.9799               am6_________       97.5535
      am7_________       98.6651               am7_________       99.6968
      am8_________       98.9949               am8_________       99.2033
      am9_________       92.8862               am9_________       94.2108
      arearech____      1.981001E-04           arearech____      1.977145E-04
   Maximum   factor change:  1.014      ["am9_________"]
   Maximum relative change: 1.4060E-02 ["am9_________"]
```

Optimisation complete: 3 optimisation iterations have elapsed since lowest phi was achieved.
Total model calls: 99

The model has been run one final time using best parameters.
Thus all model input files contain best parameter values, and model output files contain model results based on these parameters.

OPTIMISATION RESULTS

Parameters ----->

Parameter	Estimated value	95% percent confidence limits lower limit	upper limit
areak	5.64266	5.642665-300	1.000000+300
am1	103.582	1.035824-298	1.000000+300
am10	99.9692	9.996921-299	1.000000+300
am2	97.6026	9.760257-299	1.000000+300
am3	98.6343	9.863432-299	1.000000+300
am4	99.9293	9.992926-299	1.000000+300
am5	94.0570	9.405704-299	1.000000+300
am6	97.2520	9.725197-299	1.000000+300
am7	98.4015	9.840147-299	1.000000+300
am8	98.7402	9.874015-299	1.000000+300
am9	94.8604	9.486044-299	1.000000+300
arearech	1.978684E-04	-2.61107	2.61147

Note: confidence limits provide only an indication of parameter uncertainty.
They rely on a linearity assumption which may not extend as far in parameter space as the confidence limits themselves - see PEST manual.

See file best.sen for parameter sensitivities.

Observations ----->

Observation	Measured value	Calculated value	Residual	Weight	Group
a	207.750	208.052	-0.301696	1.000	head
b	206.860	208.078	-1.21810	1.000	head
c	206.880	208.083	-1.20322	1.000	head
d	208.560	208.004	0.556029	1.000	head
e	207.660	207.942	-0.281915	1.000	head
f	206.610	207.904	-1.29403	1.000	head
5503800f	10500.0	10427.6	72.4300	10.00	streamflow
5506350f	39800.0	39578.6	221.390	10.00	streamflow
5506800f	29300.0	29352.8	-52.8000	10.00	streamflow
5502500f	85300.0	85312.6	-12.6100	10.00	streamflow
5507600f	13300.0	12734.8	565.230	10.00	streamflow
mtl1	184.920	184.976	-5.630000E-02	1.000	lakestage
mtl2	184.920	184.976	-5.630000E-02	1.000	lakestage
mtl3	184.910	184.976	-6.630000E-02	1.000	lakestage
05507700	184.900	184.976	-7.630000E-02	1.000	lakestage

See file best.res for more details of residuals in graph-ready format.

See file best.seo for composite observation sensitivities.

Objective function ----->

Sum of squared weighted residuals (ie phi)	=	3.7669E+07
Contribution to phi from observation group "head"	=	23.78
Contribution to phi from observation group "streamflow"	=	3.7669E+07
Contribution to phi from observation group "lakestage"	=	1.6557E-02

```
Correlation Coefficient ----->

  Correlation coefficient                                       =  1.000


Analysis of residuals ----->

  All residuals:-
     Number of residuals with non-zero weight                           =    20
     Mean value of non-zero weighted residuals                          =   396.3
     Maximum weighted residual [observation "5507600f"]                 =   5652.
     Minimum weighted residual [observation "5506800f"]                 =  -528.0
     Standard variance of weighted residuals                            =  4.7086E+06
     Standard error of weighted residuals                               =   2170.

     Note: the above variance was obtained by dividing the objective
     function by the number of system degrees of freedom (ie. number of
     observations with non-zero weight plus number of prior information
     articles with non-zero weight minus the number of adjustable parameters.)
     If the degrees of freedom is negative the divisor becomes
     the number of observations with non-zero weight plus the number of
     prior information items with non-zero weight.

  Residuals for observation group "head":-
     Number of residuals with non-zero weight                           =    11
     Mean value of non-zero weighted residuals                          =  -1.013
     Maximum weighted residual [observation "d"]                        =  0.5560
     Minimum weighted residual [observation "a"]                        =  -3.474
     "Variance" of weighted residuals                                   =   2.162
     "Standard error" of weighted residuals                             =   1.470

     Note: the above "variance" was obtained by dividing the sum of squared
     residuals by the number of items with non-zero weight.

  Residuals for observation group "streamflow":-
     Number of residuals with non-zero weight                           =     5
     Mean value of non-zero weighted residuals                          =   1587.
     Maximum weighted residual [observation "5507600f"]                 =   5652.
     Minimum weighted residual [observation "5506800f"]                 =  -528.0
     "Variance" of weighted residuals                                   =  7.5338E+06
     "Standard error" of weighted residuals                             =   2745.

     Note: the above "variance" was obtained by dividing the sum of squared
     residuals by the number of items with non-zero weight.

  Residuals for observation group "lakestage":-
     Number of residuals with non-zero weight                           =     4
     Mean value of non-zero weighted residuals                          = -6.3800E-02
     Maximum weighted residual [observation "mtl1"]                     = -5.6300E-02
     Minimum weighted residual [observation "05507700"]                 = -7.6300E-02
     "Variance" of weighted residuals                                   =  4.1392E-03
     "Standard error" of weighted residuals                             =  6.4337E-02

     Note: the above "variance" was obtained by dividing the sum of squared
     residuals by the number of items with non-zero weight.


Parameter covariance matrix ----->

areak_______ am1_________ am10________ am2_________ am3_________ am4_________ am5_________ am6_________
am7_________ am8_________ am9_________ arearech____

areak_______   3.2271E+07  -4.4705E+07   1.1510E+08   2.5034E+08   4.4162E+06   2.4702E+08   2.7433E+07
-4.1967E+07  -5.1934E+07  -5.7261E+08   1.6527E+08    6210.

am1_________  -4.4705E+07   8.0219E+07  -1.6689E+08  -3.4397E+08  -8.2750E+06  -4.4560E+08  -1.5157E+07
5.5371E+07    9.2585E+07   8.4095E+08  -2,0078E+08   -8653.

am10________   1.1510E+08  -1.6689E+08   4.5603E+08   1.0083E+09   3.1399E+07   9.7421E+08   9.0719E+07
-1.5728E+08  -1.9467E+08  -2.3531E+09   7.7400E+08   2.3902E+04
```

```
am2________     2.5034E+08  -3.4397E+08   1.0083E+09   2.2920E+09   7.7840E+07   2.0592E+09   2.2296E+08
-3.5764E+08    -4.0734E+08  -5.3109E+09   1.8833E+09   5.3596E+04

am3________     4.4162E+06  -8.2750E+06   3.1399E+07   7.7840E+07   6.4244E+06   6.5689E+07   1.8284E+06
-9.2699E+06    -1.0385E+07  -1.9311E+08   9.3353E+07    1528.

am4________     2.4702E+08  -4.4560E+08   9.7421E+08   2.0592E+09   6.5689E+07   2.5500E+09   8.4027E+07
-3.2129E+08    -5.1884E+08  -5.0563E+09   1.3828E+09   5.0362E+04

am5________     2.7433E+07  -1.5157E+07   9.0719E+07   2.2296E+08   1.8284E+06   8.4027E+07   5.2190E+07
-3.9783E+07    -1.8633E+07  -4.4509E+08   1.8810E+08    5325.

am6________    -4.1967E+07   5.5371E+07  -1.5728E+08  -3.5764E+08  -9.2699E+06  -3.2129E+08  -3.9783E+07
5.8873E+07      6.5959E+07   8.1843E+08  -2.7584E+08   -8609.

am7________    -5.1934E+07   9.2585E+07  -1.9467E+08  -4.0734E+08  -1.0385E+07  -5.1884E+08  -1.8633E+07
6.5959E+07      1.0779E+08   9.9633E+08  -2.4975E+08  -1.0210E+04

am8________    -5.7261E+08   8.4095E+08  -2.3531E+09  -5.3109E+09  -1.9311E+08  -5.0563E+09  -4.4509E+08
8.1843E+08      9.9633E+08   1.2501E+10  -4.3730E+09  -1.2408E+05

am9________     1.6527E+08  -2.0078E+08   7.7400E+08   1.8833E+09   9.3353E+07   1.3828E+09   1.8810E+08
2.7584E+08     -2.4975E+08  -4.3730E+09   1.9264E+09   4.1181E+04

arearech____    6210.       -8653.        2.3902E+04   5.3596E+04   1528.        5.0362E+04   5325.
-8609.         -1.0210E+04  -1.2408E+05   4.1181E+04   1.282


Parameter correlation coefficient matrix ----->

areak_______   am1________  am10_______  am2________  am3________  am4________  am5________  am6________
am7________    am8________  am9________  arearech____

areak_______     1.000      -0.8786       0.9488       0.9205       0.3067       0.8611       0.6685
-0.9628         -0.8806     -0.9015       0.6628       0.9654

am1________     -0.8786      1.000       -0.8726      -0.8022      -0.3645      -0.9852      -0.2343
0.8057           0.9957      0.8398      -0.5107      -0.8531

am10_______      0.9488     -0.8726       1.000        0.9862       0.5801       0.9034       0.5880
-0.9599         -0.8780     -0.9855       0.8258       0.9884

am2________      0.9205     -0.8022       0.9862       1.000        0.6415       0.8518       0.6446
-0.9736         -0.8195     -0.9922       0.8963       0.9886

am3________      0.3067     -0.3645       0.5801       0.6415       1.000        0.5132       9.9855E-02
-0.4767         -0.3946     -0.6814       0.8391       0.5325

am4________      0.8611     -0.9852       0.9034       0.8518       0.5132       1.000        0.2303
-0.8292         -0.9897     -0.8956       0.6239       0.8807

am5________      0.6685     -0.2343       0.5880       0.6446       9.9855E-02   0.2303       1.000
-0.7177         -0.2484     -0.5510       0.5932       0.6509

am6________     -0.9628      0.8057      -0.9599      -0.9736      -0.4767      -0.8292      -0.7177
1.000
                 0.8280      0.9540      -0.8191      -0.9909

am7________     -0.8806      0.9957      -0.8780      -0.8195      -0.3946      -0.9897      -0.2484
0.8280           1.000       0.8583      -0.5481      -0.8685

am8________     -0.9015      0.8398      -0.9855      -0.9922      -0.6814      -0.8956      -0.5510
0.9540           0.8583      1.000       -0.8911      -0.9800

am9________      0.6628     -0.5107       0.8258       0.8963       0.8391       0.6239       0.5932
-0.8191         -0.5481     -0.8911       1.000        0.8286

arearech____     0.9654     -0.8531       0.9884       0.9886       0.5325       0.8807       0.6509
-0.9909         -0.8685     -0.9800       0.8286       1.000


Normalized eigenvectors of parameter covariance matrix ----->

Vector_1       Vector_2     Vector_3     Vector_4     Vector_5     Vector_6     Vector_7     Vector_8
Vector_9       Vector_10    Vector_11    Vector_12
```

areak	-5.3478E-05	4.9023E-02	0.5328	-0.5483	0.3784	-0.3548	-0.2716	-0.1031	0.1412	-0.1923	3.5607E-02	3.7143E-02
am1	1.3419E-04	0.3864	0.2930	-0.1243	0.1731	0.8287	-2.7805E-02	4.9347E-02	-2.6139E-02	2.9938E-02	-0.1575	-5.4958E-02
am10	6.3476E-05	0.3193	0.1558	0.2672	-0.2351	-0.1030	-0.3857	-0.2851	-0.6438	-0.2583	4.5260E-02	0.1526
am2	5.3494E-05	2.4218E-02	1.4392E-02	0.2193	0.1937	-5.2439E-02	-5.7313E-03	0.7481	-2.3162E-02	-0.4670	-0.1194	0.3440
am3	-1.5456E-04	-2.5051E-02	0.4498	-0.2973	-0.6368	-8.0116E-02	0.3815	0.3066	-0.1975	0.1308	-2.9502E-02	1.2522E-02
am4	4.2289E-05	-0.1014	0.3137	0.2864	6.6583E-02	0.1017	-0.1296	0.1024	0.1132	0.3768	0.7096	0.3301
am5	1.5420E-05	-0.1972	0.4191	0.4317	-9.2993E-02	6.9343E-02	0.3246	-0.3883	0.3563	-0.4348	-0.1128	2.8344E-02
am6	-8.9803E-06	2.9947E-02	0.1148	0.1211	0.5548	-0.1524	0.5982	-7.0229E-02	-0.4944	0.1736	5.2130E-03	-5.3003E-02
am7	-8.4248E-05	-0.8256	0.1259	-4.4408E-02	7.7334E-02	0.2590	-0.2694	2.8456E-02	-0.3478	4.9248E-03	-0.1702	-6.5090E-02
am8	4.7609E-05	8.8398E-02	0.2426	0.3435	2.5901E-02	-0.1512	-0.2051	0.2917	4.0435E-02	6.0102E-02	4.5236E-02	-0.8108
am9	3.3645E-05	7.5247E-02	0.2038	0.2703	3.1021E-02	-0.1979	-0.1910	2.6144E-03	0.1363	0.5436	-0.6399	0.2822
arearech	-1.000	1.4336E-04	-2.1536E-05	1.3415E-04	8.9020E-05	1.0428E-04	-7.2309E-05	-2.7814E-06	2.7903E-05	-1.8881E-05	1.1873E-06	8.0433E-06

Eigenvalues ----->

4.3898E-13	5.3785E-06	1.0041E-05	1.3541E-05	3.9236E-05	342.9	8.5796E+04	2.1663E+06	6.3011E+06	1.2781E+08	9.1351E+08	1.9013E+10